“Disentangling the climate change impacts on productivity and availability for *Macruronus* species”

Claudio Castillo-Jordán (B.Sc., M.Sc.)

Quantitative Marine Science, Institute for Marine and Antarctic Studies

Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

University of Tasmania

February 2017

Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of the my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Claudio Castillo-Jordan

Signed____________________

Date____ 8 February 2017______

Statement of Access

The publishers of the paper comprising Chapter 2 hold the copyright for that content, and access to the material should be sought from the journal. The remaining non-published content of the thesis may be made available for loan and limited copying and communication in accordance with the Copyright Act 1968.

Claudio Castillo-Jordan

Signed____________________

Date____ 8 February 2017______

Statement of Ethical Conduct

The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of the Gene and Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

Claudio Castillo-Jordan

Signed____________________

Date____ 8 February 2017______

Workshops and conferences attended informing research approach, and presentations resulting from research completed during candidature

2013 Oral presentation:

Management Implications of Including a Climate-Induced Recruitment Shift in The Stock Assessment for Patagonian Grenadier (*Macruronus Magellanicus*) in Chilean Patagonia. ICES/NAFO symposium, 15-18 October 2013. St Andrews, New Brunswick, Canada.

2014 Oral presentation:

Co-incident recruitment patterns of Southern Hemisphere fisheries. Johan Hjort Symposium October 2014. Bergen, Norway

2016 Oral presentations:

From the other side of the Pacific Ocean: environmental indicators and recruitment of Grenadiers in Chile and Australia. 7th World Fisheries Congress 2016. Busan, Korea.

Adviser/collaborator National Research Institute of Fisheries Science, Japanese Fisheries Research and Education Agency, analyzing egg and larval surveys and environmental factors. Project Spatial and temporal dynamics of spawning habitat of small pelagic fish in the Kuroshio Current system. Supervisor Dr. Akinori Takasuka. May 2016, Yokohama, Japan.

Authorship and Contributions

The candidate contributed between 65-75% to each of the chapters in this thesis, including acquisition of data, study design, analysis and writing. This thesis is written in chapters, thus the reader can expect some repetitions in the thesis.

The relative author contribution of each research chapter (2-4) is summarized below, with the candidates name in **bold**

Chapter 2 has been published as

Castillo-Jordán, C., Klaer, N.L., Tuck, G.N., Frusher, S.D., Cubillos, L.A., Tracey, S.R., Salinger, M.J., 2016. *Coincident recruitment patterns of Southern Hemisphere fishes*. Can. J. Fish. Aquat. Sci. 73 (2): 270–278.

C. Castillo-Jordan (65%)

N. Klaer (10%)

G.N. Tuck (8%)

S. Frusher (8%)

L. Cubillos (3%)

S.Tracey (3%)

J. Sallinger (3%)

Details of authors' roles

N. Klaer: guidance processing and interpreting fisheries data, conceptual development, editing and review

G.N. Tuck: guidance processing and interpreting fisheries data, conceptual development, editing and review

S. Frusher: conclusion, editing and review.

L.Cubillos: guidance, editing and review

S.Tracey: guidance, editing and review

J. Sallinger: guidance processing environmental data, general conclusions.

We the undersigned agree with the above stated 'proportion of work undertaken' for each of the above-published peer-reviewed manuscripts contributing to this thesis:

Signed: _

Professor Stewart D. Frusher

Supervisor

Institute for Marine and Antarctic Studies

University of Tasmania

Date____ 8 February 2017______

Acknowledgements

I would like to thank the Chilean Government Scholarship program “Becas Chile” under the Resolución Exenta Nº 2746/2013 for providing a scholarship to support my research and living allowance in Australia. I also thank the Quantitative Marine Science PhD program for providing a top up scholarship and international conference support (Canada 2013) and the Institute of Marine and Antarctic Studies (IMAS) for international conference support (Norway 2014 and Korea 2016). Many thanks to CSIRO that have provided international conference support as well (Canada 2013, Norway 2014 and Korea 2016). Thanks to the stock assessment team at CSIRO (Geoff, Neil, Sally, Jemery, Malcolm, Andre, Rich, Robin, Miriana and Judy). I joined the team in April 2013 and they made me feel welcome from the beginning, giving suggestions and advice about my research. CSIRO community, footy kickers, AFL9, Joga Bonito team, IMAS-UTAS PhDs, Chileans in Hobart, and Hobartians communities many thanks; you have been awesome during my Aussie life.

I thank my team of supervisors – Stewart Frusher, Geoff Tuck, Sean Tracey and Paul Hamer – for their input and support. Especially to Stewart that proposed to me come to Tasmania almost 7 years ago (Japan 2010), and Geoff that have been a strong support at CSIRO and outside CSIRO. To the Families Hadley-Leeds and Tuck-Moate that have helped to do the winters warmer and the summer more refreshing during my time in Hobart.

Finalmente quiero agradecer a mi familia en mi lengua materna, ya que ellos han sido los mas perjudicados con mis estudios, al estar lejos y no poder estar presente en algunos momentos difíciles. Muchas gracias a mi linda Suri por soportar la distancia durante este tiempo de estudio. Gracias totales (V2.0)!!

Table of Contents

Table contents

Figure contents

Thesis Abstract

Fish populations are impacted by a variety of processes including physical (temperature, salinity, currents), biological (growth, mortality) and human impacts (harvest). Most fish species exhibit a pre-recruitment or larval phase that is impacted by stochastic environmental factors which results in year to year variability in biomass. Importantly overlying annual recruitment can be long term trends, such as climate change, which require different approaches to management. Understanding the drivers for recruitment variability, especially the larval phase, provides an opportunity to build these relationships into traditional fisheries models to improve stock assessment and provide greater confidence to future projections. A crucial need for the appropriate management of marine resources is to have projections of sustainable harvests. For fisheries management, information to determine the limit and target catch levels are necessary to ensure a sustainable fish stock and industry.

This thesis investigated recruitment variability in fisheries. The first data chapter (Chapter 2) explores commonality in recruitment patterns in a range of Southern Hemisphere commercially fished species to determine any common recruitment signals. We tested three climate indices: the Inter-decadal Pacific Oscillation (IPO), Southern Annular Mode (SAM) and Southern Oscillation Index (SOI) to explore their relationship with fish stock recruitment patterns. The time-series of IPO and SOI showed the strongest correlation with New Zealand hoki (blue grenadier) and Australian jackass morwong (r= 0.50 and r= -0.50), and SAM was positively related to Australian Macquarie Island Patagonian toothfish (r= 0.49). This chapter has been published in the Canadian Journal of Marine and Fisheries Science as “Coincident recruitment patterns of southern hemisphere fishes” (73(2): 270-278, 10.1139/cjfas-

2015-0069). In Chapter 3 I focused on fine scale recruitment patterns at the level of a single species focusing on the Patagonian grenadier fishery. The Patagonian grenadier stock in Chile appears to have undergone rapid biomass depletion related to changes in recruitment and thus provided an ideal case study to investigate fine scale recruitment changes in a fishery. To be able to evaluate the impact of future recruitment scenarios on future catches of Patagonian grenadier, I developed an age-structured Stock Synthesis assessment model using data from 1985 to 2013 (Chapter 3).

The Stock Synthesis assessment modelling platform allows the use of all the data available for the fishery including different fleets operating across different spatial regions and during different years. The model was validated against the existing stock assessment model and sensitivity testing demonstrate it is suitable in describing the status of the stock. The stock synthesis model was then used to evaluate changes in recruitment that had been documented in the fishery. I compared two scenarios: Scenario 1 is the standard assessment approach that uses the entire recruitment data from 1985 and treats recruitment as a stationary variable that assumes recruitment varies around an equilibrium trend. Scenario 2 is a two-phased stock recruitment curve that splits the recruitment time series into two distinct periods with differing productivity, associated with a climate change induced regime shift in the late 1990s.

Using the assessment model developed in Chapter 3, I evaluated different management strategy scenarios for future sustainability of the Chilean Patagonian grenadier fishery and compared different future outcomes based on whether a shift in stock recruitment had or had not occurred (Chapter 4). A Management Strategy

Evaluation (MSE) procedure was implemented to examine the consequences of incorporating a different model structure for recruitment values in the assessment which underpins the harvest strategy used to set the annual total allowable catch (TAC). A management strategy that does not consider a shift in recruitment resulted in average TAC values of approximately 125,000 tonnes, substantially above the sustainable yield of 45,000 tonnes when the recruitment shift was incorporated. A TAC based upon No Shift in recruitment would lead to unsustainable catches with significant impact on the ecosystem as well as the industry and coastal communities reliant on the industry if there was an actual shift in recruitment. The history of the Patagonian grenadier fishery demonstrates the benefits of taking a precautionary approach that accounts for the change in fish productivity (whether climate-driven or otherwise). However, there can be considerable delays before a regime shift is observed in the recruitment data or an assessment model mis-specification is detected.

Chapter 1

1 GENERAL INTRODUCTION

Fisheries and environment

The total global wild caught seafood production is estimated at 81.5 million tonnes, with the majority coming from marine waters. Fisheries and aquaculture play an important role as a food supplier, employment creator, and income generator and for food and nutrition security (FAO 2016). Thus changes in the abundance of marine resources can have significant implications for both the utilisation and conservation of these resources. Optimal utilization of fisheries resources will be essential to meet the increased food demand from a growing global population (Rice and Garcia 2011). Importantly, the majority of the main fishable global resources are near maximum production or overfished, and thus any declines in abundance will need to be addressed quickly to ensure sustainability.

Fluctuations in resource abundance can be driven by a range of physical and biological events such as seawater temperature, ocean and coastal currents, changes in maturity, etc (Mann 1993; Hofman and Powell 1998; Hsieh et al. 2006; Shelton and Mangel 2011). These events have normally been considered to be stationary in that they vary around a mean that is static over time. However, climate change is becoming increasingly recognized as a factor that can affect a range of processes in marine ecosystems and which results in non-stationarity of impacts. For example, if larval survival is lower in warmer waters (e.g. thermal tolerance, prey or predation mismatches) resulting in lower recruitment than average to the fishery, then the average recruitment would be expected to decline over time if warmer years become more often (e.g. *Theragra chalcogramma* (Mueter et al. 2011). In addition to abundance, climate change may also affect the distribution and phenological changes in marine populations that would have flow-on impacts to ecosystem interactions including the conservation of biodiversity (Doney et al. 2012; Todd et al. 2012; Visser & Both 2005).

Fish populations can respond in different ways to climate variation. For instance, physiological changes could be produced by environmental factors such as local water temperature. Pörtner and Knust (2007) showed how the reduction in aerobic scope, which is produced by thermal limitation, could limit the energy for growth performance, development, fecundity, recruitment and life style. These changes in ecosystem interactions can also indirectly impact commercially important marine resources through alteration of productivity, structure and ecosystem composition (Brander 2007).

Fish variability

The dynamics of fished species vary between years due to variability in a number of key life history traits (growth, reproductive capacity, survival rate, etc). This variability produces considerable uncertainty in the dynamics of marine resources which needs to be captured for their sustainable management. Given that most fish rely intimately on the physical characteristics of the oceans (e.g. ocean currents, water temperature) to grow, survive, reproduce and distribute their offspring, climate variation should be considered in fishery stock assessments as part of the traditional modelling and assessment frameworks. Hollowed et al. (2008) show a framework for modelling fish responses including climate change variables. Adding environmental variables to assessment models has the potential to improve modelled scenarios and the prediction of fish stock dynamics, and incorporate a greater level of conservatism to account for the uncertainty of climate change impacts.

Recruitment in fisheries science is used differently throughout the literature and in this thesis, it will be defined as "post-larval recruitment" where larval animals recruit to the juvenile or adult habitat (e.g the seabed). Demersal fish may use both pelagic and demersal habitats depending on their life-history. For many demersal fishes the early life stages (eggs and larvae) typically use the pelagic habitat, and the later stages (juvenile and adult) typically live in demersal habitats (Rijnsdorp et al. 2009). Several hypotheses have been formulated by various authors to explain the process of recruitment variation including: the role of starvation and predation (Hjort 1914; Lasker 1978; 1981; Rothschild & Osborne 1988); the match-mismatch between prey availability and larval period/occurrence (Cushing 1975; Cushing 1990; Rothschild & Osborne 1988), advection/dispersal/retention into/away from suitable larval rearing environments by wind and ocean driven currents (Parrish et al. 1983), and integrated hypotheses frameworks such as the optimal environmental window (Cury & Roy 1989) and the triad hypothesis (Bakun 1996). Environmental processes can have variable consequences for different species and life stages, which are often manifest in variable recruitment dynamics.

Long-term changes in climate and/or the dynamics of climate variation may create instability in aspects such as growth and mortality rates, the dynamics/frequency of high and low recruitment events, changes in stock distributions, and changes in stock-recruitment relationships. While most fisheries assessments are configured with assumptions that the stock-recruit relationship is stationary overtime, recent studies have hypothesised that large and permanent changes in recruitment are linked with climate change (A'mar et al. 2009, Wayte et al 2013). Such changes are referred to as regime shifts.

Regime shifts are low-frequency, high-amplitude changes, in oceanic conditions that may have especially pronounced effects on biological variables and propagate through several trophic levels (Collie et al. 2004). It is known that regime shifts occurred in the early 1970s and mid 1980s, leading to changes in abundance of anchovy and sardine in the Southeast Pacific (Chavez et al. 2003; Alheit and Niquen 2004). Having a greater understanding of the cause(s) of regime shifts is important to allow managers to be able to appropriately adjust fishing effort to match the shifts in productivity of the ocean environment (Rothschild and Shannon 2004).

Grenadier fishery

The family Merluccidae is part of the gadoid group, which is divided into two subfamilies: *Merlucciinae* and *Macruroninae* (Lloris et al. 2005). The genus *Macruronus* has a limited distribution in the Southern Hemisphere with total landings reported at the end of 20th century was approximately 700,000 tonnes (FAO 2005 cited in Lloris et al. 2005). It is divided into two species: Blue Grenadier or Hoki (*Macruronus novaezelandiae novaezelandiae*) and Patagonian Grenadier (*Macruronus novaezelandiae magellanicus*). The names Blue Grenadier and Hoki will be used throughout this thesis for Australian and New Zealand fisheries respectively, and the names Patagonian Grenadier and Patagonian Hoki for the Chilean and Falkland Island fisheries respectively.

Grenadiers from South America

Macruronus magellanicus is the most abundant gadoid resource in Chilean Patagonia (41º40' to 52ºS) (Tascheri et al. 2010) and is also an important resource for Argentina (Ministerio de Agricultura 2012) and the Falkland Islands (Falkland Islands Government, 2013). The species occurs in two geographical areas: the Southeast Pacific between Valparaíso (33º S) and Cape Horn (55º 58' S) in Chile (Arana 1970 cited in Prenski et al. 2012), and in Argentina in the Southwest Atlantic between 33º S and 57º S (Wölhler and Giussi 2001 cited in Schuchert et al. 2010). Over the last decade, the total annual catch of Patagonian hoki in waters off the Falkland Islands has varied between 16,000 and 26,000 tonnes (average 20,500 tonnes per year) showing no consistent trend over time (Falkland Island Government 2013).

Grenadier from New Zealand and Australia.

Blue grenadier also support important commercial trawl fisheries in Australian and New Zealand waters (Gunn 1989; Punt et al. 2001b; Francis et al. 2006). Blue grenadier is found from New South Wales around southern Australia to Western Australia, including Tasmania (Tuck 2012), and most blue grenadier taken in Australian and New Zealand waters are captured by trawl from depths between 300 and 600 m with the majority of the catch taken from the 450 to 550 m depth range (Hamer et al. 2012, McKenzie 2016). In 2015/16, the Total Allowable Catch (TAC) for this species was set at 8,796 tonnes (Patterson et al. 2016). In the period 2015, McKenzie (2016) reported that New Zealand fisheries caught 160,000 tonnes of Hoki. In Australia, Blue grenadier recruitment has been highly variable with strong year-classes in 1972, the mid 1980s, 1994, 2003 and 2006 and poor recruitment between 2007 and 2011(Tuck 2012). The Hoki recruitment in New Zealand is less variable than Australia with near or above average recruitment since 2001, with the exceptions of 2010, 2012 and 2013 when it was below the average (McKenzie 2016).

Fish fluctuation and environment.

The Patagonian grenadier has shown a decline in biomass in recent years (Paya and Canales, 2011). According to Paya and Canales (2011), the decline in biomass started in 2004, and was preceded by a considerable reduction in recruitment from 1999. This reduction was correlated with a shift to colder sea surface temperatures in the main spawning/nursery areas of the species (Cubillos et al. 2014). Schneider et al. (2017) identified that physical and biological changes have been occurring in the waters off central-south Chile. The physical changes include changes in wind, temperature and salinity, and the biological changes by altered plankton communities and declining plankton biomass (Schneider et al. 2017).

Links between the environment and fish stocks were initially undertaken on a case-by-case basis focused on individual fish stocks. To date most studies have focused on the Northern Hemisphere where various researchers have found relationships between fisheries and oceanographic variables (Koslow 1984; Hollowed et al. 2001; Brunel and Boucher 2007; Stachura et al. 2014). For example, correlative studies have been used to look at relationships between recruitment time series and oceanographic factors, such as salinity (Koslow 1984), water temperature, wind stress, shelf water volume anomalies (Brodziak and O'Brien 2005) and NAO, Sea Surface Temperature (SST) (Brunel and Boucher 2007). These environmental variables, including the direct effects of climate change, can increase the uncertainty of the dynamics of fish populations and their associated fisheries. In addition, this climate variability changes can have an impact on marine resources leading to fluctuation in abundance (McFarlane et al. 2000; King 2005). A review of methods to incorporate regime shifts in stock assessment and management of marine resources has been developed by King and McFarlane (2006). These authors identify the difficulties and propose potential frameworks that incorporate regime shifts into management and assessment. Recent studies have incorporated regime shifts in the stock assessment process for different species. A'mar et al. (2009) studied the impact of a regime shift in the North Pacific Ocean on management strategies for walleye pollock (*Gadus chalcogrammus*). In Australia, a study of jackass morwong (*Nemadactylus macropterus*) (Wayte, 2013) used Management Strategy Evaluation (MSE) to assess the consequences of mis-specifying a regime shift that produced changes to the average level of recruitment.

Thesis summary

This thesis shows recruitment patterns across a range of Southern Hemisphere commercially fished species to determine common broad-scale recruitment signals (chapter 2). Then I investigated recruitment variation using the Chilean Patagonian grenadier stock assessment (chapter 3) and a Management Strategy Evaluation for the fishery (chapter 4) as a case study to explore recruitment dynamics at a local scale.

To compare broad scale recruitment patterns, I collected recruitment data from 30 stocks across Australia, New Zealand, Chile, South Africa and the Falklands Islands (Chapter 2). Chapter 2 has been published in the Canadian Journal of Marine and Fisheries Science as *Coincident recruitment patterns of southern hemisphere fishes*. The following chapter focused on Chilean Patagonian grenadier fishery. The Patagonian grenadier stock in Chile appears to have undergone rapid biomass depletion related to changes in recruitment and thus provided an ideal case study to investigate fine scale recruitment changes in a fishery. To be able to evaluate the impact of the future recruitment scenarios on future catches of Patagonian grenadier, I developed an age-structured Stock Synthesis assessment model (Chapter 3). This stock assessment modelling platform allows the use of all the data available for the fishery to determine the implications of a regime shift in the recruitment time series. I used the model to best fit the data and then use standard statistics to evaluate performance (Methot and Wetzel 2013) using both the historical recruitment data assuming the average recruitment curve for the entire recruitment time series as well as a two phase stock recruitment curve that splits the recruitment time series into two distinct periods that could be associated with a climate change induced regime shift. Using the assessment model, I evaluated different management strategy scenarios for the future sustainability of the fishery, assuming that the assessment model was based on the entire average recruitment or a regime shift stock recruitment situation (Chapter 4). Finally, in Chapter 5 I discuss the overall implications of environmental impacts from global and basin-scale impacts on fisheries in general, to regional and local impacts on single species and outline some of the issues for global fisheries production.

Chapter 2

2 COINCIDENT RECRUITMENT PATTERNS OF SOUTHERN HEMISPHERE FISHES.

2.1 Abstract

Three dominant recruitment patterns were identified across 30 stocks from Australia, New Zealand, Chile, South Africa and the Falkland Islands using data from 1980 to 2010. Cluster and dynamic factor analysis provided similar groupings. Stocks exhibited a detectable degree of synchrony among species in particular, the hakes and lings from Australia, New Zealand, Chile and South Africa. We tested three climate indices: the Inter-decadal Pacific Oscillation (IPO), Southern Annular Mode (SAM) and Southern Oscillation Index (SOI) to explore their relationship with fish stock recruitment patterns. The time-series of IPO and SOI showed the strongest correlation with New Zealand hoki (blue grenadier) and Australian jackass morwong ($r= 0.50$ and $r= -0.50$), and SAM was positively related to Australian Macquarie Island Patagonian toothfish ($r= 0.49$). Potential linkages in recruitment patterns at sub-basin, basin and multi-basin scales and regional and global climate indices do account for some of the variation in recruitment, playing an important role for several key Southern Hemisphere species.

2.2 Introduction

Both exploited and non-exploited marine living resources show considerable variation in abundance over time (Hsieh et al. 2006; Anderson et al. 2008; Shelton and Mangel 2011; Ohlberger et al. 2014). Natural variability can occur at the adult stage through fluctuations in recruitment flowing into adult abundance, or from ecosystem processes such as predation, competition, or food and suitable habitat availability. For fish populations, recruitment variability is commonly considered one of the largest drivers of fluctuations in abundance (Shelton & Mangel 2011). The variability in recruitment to a fished stock has implications for stock assessments and subsequent sustainable fisheries management, especially in short-lived stocks (e.g. sardines and anchovies) or where recruitment shows large variations, with long periods between recruitment episodes (blue grenadier and pacific ocean perch) (Leaman, 1991; Punt et al., 2001b).

Incorporation of stock variability into assessment models can reduce the risk of biases associated with steady-state assumptions; subsequently decreasing the potential for significant economical, biological and political ramifications (Beddington et al. 1984; Caddy 1984; Steele 1984; Walters 1984; Myrseth et al. 2011).

Environmental processes are a key component affecting recruitment to fished stocks, and range from impacts that influence larval dispersion and survival (Cury & Roy 1989; Bakun 1996) to impacts on physiology through changes in aerobic scope that limit energy and growth performance, development, fecundity, recruitment and life style (Pörtner and Knust 2007). While early research focused on smaller scale processes associated with modelling nutrients and associated primary productivity, particularly around small pelagic fisheries (Cury & Roy 1989; Cury et al. 2000; Palomera et al. 2007), recent studies have switched consideration to the influence on larval survival of large ocean-wide processes measured by indices such as the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), and the Southern Oscillation Index (SOI) (Hollowed et al. 2001;

Brunel and Boucher 2007; Salinger 2013; Stachura et al. 2014). The interest in exploring the potential of these basin-scale drivers has evolved due to an increased recognition of longer-term global and regional scale environmental changes and their effect on fishery productivity (Cheung et al. 2009; Cheung et al. 2010). While understanding these indices has aided in the interpretation of change at regional scales, there is limited knowledge for fisheries and climate indices at multi-basin scales, especially in the Southern Hemisphere (Koslow 1984; Hollowed et al. 2001; Mantua et al. 1997).

Links between the environment and fish stocks were initially undertaken on a case-by-case basis focused on individual fish stocks. To date most studies have focused on the Northern Hemisphere where various researchers have found relationships between fisheries and oceanographic variables (Koslow 1984; Hollowed et al. 2001; Brunel and Boucher 2007; Stachura et al. 2014). For example, correlative studies have been used to look at relationships between recruitment time series and oceanographic factors, such as salinity (Koslow 1984), water temperature, wind stress, shelf water volume anomalies (Brodziak and O'Brien 2005) and NAO, Sea Surface Temperature (SST) (Brunel and Boucher 2007). More recently, recruitment strength has also been compared with larger scale indices such as the El Niño Southern Oscillation (ENSO), and PDO (Hollowed et al. 2001). In addition, North Atlantic Oscillation (NAO), Atmospheric Circulation Index (ACI), Northern Hemisphere Temperature anomaly, Artic Oscillation Index, North Pacific Gyre Oscillation and North Pacific High Pressure Index were found to influence the abundance of 34 northeast pacific stocks of Salmon (Stachura et al. 2014).

There is considerable uncertainty in correlating oceanic indices and fish recruitment patterns, and greater certainty in understanding the drivers may occur from comparing outcomes from different statistical approaches. Dynamic factor analysis (DFA), a method used to find common trend(s) in several time series (Zuur et al. 2003a), has been used to understand variation in recruitment in European (Zuur et al. 2003a; Zuur et al. 2003b; Zuur and Pierce 2004; Erzini 2005; Ligas et al. 2011) and North American fish stocks (Stachura et al. 2014), where common trends amongst a number of time series were found (Zuur et al. 2003a; Zuur et al. 2003b; Zuur and Pierce 2004; Erzini 2005; Ligas et al. 2011; Stachura et al. 2014). Cluster analysis (CA) examines the hierarchical relationships of fish stocks based on similarity of their attributes. CA has been applied largely in the Northern Hemisphere, for example populations in the Northeast Pacific (Mueter et al. 2007), North Eastern Atlantic fish populations (Brunel and Boucher 2004) and Northwest Atlantic fish-stock abundance variation (Rothschild and Jiao 2012).

In this paper we consider 30 stocks from Australia, Chile, New Zealand, South Africa and the Falkland Islands covering three ocean basins (Southern Indian, Pacific, and Atlantic Oceans). The fish stocks range from benthic, to semi-pelagic to bathydemersal, and from short-lived (school whiting) to long-lived (jackass morwong, toothfish). The fish stocks considered are generally of substantial economic importance in their respective countries. The grenadiers are important by tonnage for Australia, New Zealand and Chile, and the hakes are the most valuable for South Africa (Flood et al. 2013; Ballara and O'Driscoll 2014; Sernapesca 2014; www.msc.org).

The objective of this study is to use both statistical methods to improve our understanding of commonality between patterns in recruitment across these stocks and to evaluate their potential relationship with broad scale climate indices.

2.3 Materials and methods

2.3.1 Biological data

Recruitment residuals at age zero (response variable) were obtained using a fitted stock recruitment relationship for 30 commercially important species from Australia, New Zealand, South Africa, the Falkland Islands and Chile; from stocks with full stock assessments following the method described in Methot and Taylor (2011). A summary of the time series data of the recruitment residuals for each stock assessed is presented in Table 2.1. Residual data from Australian stocks were obtained from a standardised stock assessment method using Stock Synthesis (Methot 2000; Methot and Wetzel 2013). New Zealand and the Falkland Island data were obtained from a standardised stock assessment method using CASAL (Bull et al. 2008) and year class strength (YCS) was converted to recruitment residuals using a logarithmic scale. Chilean and South African data are outputs from age-structured stock assessment models (Chilean fisheries institute IFOP; Rademeyer and Butterworth 2013). All data used assumed a Beverton and Holt (1956) stock-recruitment relationship that was fitted using a lognormal error distribution. In order to compare trends between species each data time series was standardized to have a mean of 0 and a standard deviation of 1.

2.3.2 Climate indices.

Three climate indices relating to the Southern Hemisphere were selected to analyse their relationship with the recruitment patterns: the Inter-decadal Pacific Oscillation (IPO), Southern Annular Mode (SAM) and Southern Oscillation Index (SOI). The Interdecadal Pacific Oscillation (IPO) is the Pacific-wide manifestation of the Pacific Decadal Oscillation (North Pacific only), with as much variance in the Southern Hemisphere Pacific to at least 55^{o}S, as in the Northern Hemisphere. The IPO modulate El Niño Southern Oscillation (ENSO) climate teleconnections to Australia (Power et al. 1999) and New Zealand (Salinger et al. 2001). Warm phases characterised the 1920s to 1940s and the mid-1970s to at least the 1990s. In these periods ENSO was a weaker source of interannual climate variability. They were preceded and separated by IPO and PDO cool phases from the 1900s to 1920s and 1940s to 1970s, then since 1999 when ENSO was a major source of interannual climate variability (Deser et al. 2004). IPO data were obtained from the Climate of the 20th Century project (http://iges.org/c20c/). The SAM is the leading mode of atmospheric variability south of 20°S (Karoly et al. 1996; Thompson and Wallace 2000; Trenberth et al. 2005). It appears at all time-scales from daily to interannual, and consists of a fluctuation in atmospheric pressure between the Antarctic region and the southern mid-latitudes. In the positive phase of the SAM, anomalous low pressure occurs over Antarctica (mid-latitudes). The mid-latitude westerly wind maximum and the tracks of extra tropical storms (Yin 2005; Kidston and Gerber 2010) also shift toward the pole (the equator) during the positive phase of the SAM. In recent years, a high positive SAM has dominated during autumn–winter and has been associated with a systematic regime transition in the Southern Hemisphere mid-tropospheric circulation post the late 1970s (O'Kane et al. 2013). SAM data were sourced from the

Annular Mode Website (www.atmos.colostate.edu/ao/). SOI is an index formed from surface pressure differences across the South Pacific (Ropelewski and Jones 1987). When the SOI is strongly negative, anomalously warm surface waters appear off the coasts of Peru and Ecuador. This is called "El Niño," while the reverse condition with a strong positive SOI and anomalous cold surface waters is called "La Niña" (Salisbury and Wimbush 2002). SOI data was obtained from the Climate Prediction Center NOAA (http://www.cpc.ncep.noaa.gov/data/indices). The SOI is negatively correlated with IPO (r=-0.66). There are no other strong correlations among the indices.

2.3.3 Cluster Analysis

Cluster analysis (CA) allows groups of species to be defined based on common similarity in their attributes. Similarity across species was measured here using the Ward.D2 method (Maechler et al. 2014). The recruitment residuals dataset (Table 2.1) is depicted as a scatter of points, identifying which species recruitment time series data are more similar according to the distance between them. The resulting groupings of species show high homogeneity within the cluster and high heterogeneity externally (Hair et al. 1984). Species in the same group tend to cluster closely together in the geometrical graph with considerable distance between groups. Thus, identifying the different clusters between species makes it possible to identify a common group, and possible common patterns in recruitment residuals within groups. The number of groups is determined according to the appropriate distance between the species. CA was performed using the R software (R Development Core Team 2012) with the Cluster Analysis package (Maechler et al. 2014).

2.3.4 Dynamic Factor Analysis

DFA is a dimension reduction technique specific for time-series data that can indicate if multiple time-series have common underlying patterns. (Zuur et al. 2003a, b). DFA was used to identify common trends and to model the recruitment deviation trends among stocks in terms of a linear combination of common tendencies (Zuur et al. 2003a). DFA uses the common patterns among N time series to be characterized with M trends (Zuur et al. 2003b; Zuur and Pierce 2004).

The level parameters indicate the relationship in the time series, with positive and negative loadings representing positive and negative correlations with DFA trends respectively. The magnitude of the level parameters reflects the amount of variance explained by the model trend. Three forms of the observation error variance and covariance were tested: (1) considering the same variance and no covariance (diagonal and equal), (2) different variances and no covariance (diagonal and unequal) and (3) the same variances and covariance (equalvarcov) (Holmes et al. 2012). The best model was selected using a second order Akaike's information criterion (AICc) to determine the number of trends in the period analysed, taking into account the sample size (Burnham and Anderson 2002). DFAs were performed using the R software (version 3.0.0; http://www.r-project.org/) with the MARSS package (Holmes et al. 2012).

2.3.5 Correlation between recruitment residuals/DFA trends and climate indices.

A Pearson correlation coefficient was used to determine the degree of correlation between recruitment residuals and climate indices. Multiple tests were conducted, and a Bonferroni correction was applied to adjust the level of significance of the multiple inferences (Baudron et al 2014). The analysis was performed using the psych package (Revelle 2015). The relationship was considered significant if the correlation had a p-value less than 0.05. The p-values presented do not account for autocorrelation.

2.4 Results

2.4.1 Cluster Analysis

Groupings from the cluster analysis showed that species with common patterns tended to aggregate at both regional-species and Southern Hemisphere-species combinations. This suggests that there are both regional and global influences on recruitment patterns across multiples species. Five clusters were identified (Fig. 2.1). Cluster 1 included species from Australia, South Africa and Chile, dominated by species from continental shelf and slope waters (e.g. AUWARE, SADHAK); Cluster 2 included species mainly from Australia and three from New Zealand, with the Australian species typically from continental shelf and slope habitats, except for AUSHW which is distributed close to the coast; Cluster 3 included hakes from New Zealand, Chile and South Africa; Cluster 4 included lings from Australia, New Zealand and Chile, and Cluster 5 included a mix of species – both New Zealand toothfish, grenadiers from New Zealand and Australia, two flathead species from Australia and south pacific hake and west coast ling from Chile and Australia. Group placements of toothfish from the Falkland Islands, Chile and Australia appear to be less intuitive in Clusters 1, 2 and 4 respectively according to the species distribution group.

There were common species patterns at regional (sub-basin), within oceans (basin) and across oceans (multi-basin) scales. Ling stocks (Fig. 2.4) showed a similar trend within regional water masses. At the Tasman Sea scale that separates Australia from New Zealand, both Australian and southern ((NZLIN6B) and west coast New Zealand (NZLIN7) ling stocks showed similar recruitment trends. Similarly, at the southern Pacific Ocean scale that links New Zealand to Chile, east and southeast coast New Zealand (NZLIN34 and NZLIN56) and Chilean ling stocks showed a similar trend. In contrast, hakes showed multi-ocean scale commonalities with Chilean (Southern (CHHAK) and South Pacific (CHPHAK)), New Zealand (NZHAK1, NZHAK7 and NZHAK4) and South African (SASHAK) hakes all having similar recruitment trends.

2.4.2 DFA

The most parsimonious model identified by DFA that described temporal variation in the recruitment deviation (RD), included three trends with the same variance and no covariance (Model 3a, Table 2.2).

The first common trend (Trend 1) presented a steep decline from the start of the time series in 1980 to 1998, followed by a positive period from 1999 to 2010, declining at the end of the time series. Trend 1 is dominated by Cluster 1, with the main species showing a negative relationship with factor loading values of -0.25 (Fig. 2.2).

The second common trend (Trend 2) showed small fluctuations around zero from 1980 to 1990, then from 1991 to 2002 there was a rapid decrease after which there was a gradual increase. At the end of the time series Trend 2 decreased gradually. This trend is mainly dominated by hakes, which show strong positive loading with values between 0.2 and 0.4 approximately. In addition, Trend 2 presents a similar result to cluster 3 from the cluster analysis (Fig. 2.2).

The third common trend (Trend 3) showed low stable values from 1980 to 1990. From 1991 to 1996 there was a rapid increase after which there was a continuing decrease until 2000. After 2000, this trend had a short recovery, followed by a rapid decline towards the end. This trend presented a mix of species predominantly from Australia and New Zealand and mainly corresponded to Cluster 2 where it was negatively correlation (Fig. 2.2). In addition, Trend 3 showed a related pattern to Cluster 4 (Fig. 2.2) that include lings from Australia, New Zealand and Chile, all contained in Cluster 4 with a positive relationship and factor loading between 0.19 and 0.45.

The recruitment residuals for the individual species were well fitted by the DFA trends, except for a few species, such as tiger flathead (AUFLT) and blue grenadier (AUGRE), that showed a flat curve (Fig. 2.4).

2.4.3 Correlation between recruitment residuals/DFA trends and climate indices.

The global atmospheric and climate indices IPO and SOI were generally well correlated with the recruitment deviations of jackass morwong, silver warehou and New Zealand grenadier (Table 2.3). IPO was strongly correlated with all grenadiers with values from 0.39 to 0.50 and also had a high correlation with toothfish from the Falklands Islands. SAM was well correlated with Australian toothfish, Southern New

Zealand ling and New Zealand blue grenadier. Finally, SOI showed a negative correlation with Chilean Pacific hake.

Trend 1 detected by DFA analysis showed a strong negative correlation with IPO (r=-0.41), Trend 2 is positively correlated with SAM (r=0.31) and Trend 3 is negatively correlated with SOI (r=-0.32) (Fig. 2.3, Table 2.3). This provides an indication that underlying recruitment trends as detected by DFA using recruitment residuals alone are indeed consistent to some extent with each of the environmental series examined. An extension to cluster groupings is that species in C1 show a stronger consistency with IPO, C3 by SAM, C2 and C4 by SOI (Fig. 2.2).

2.5 Discussion

Our results suggest that there are common trends in recruitment patterns within and between ocean basins. Apparent physical-biological synchronies between the Pacific and Atlantic basins have been described by Alheit and Bakun (2010). They conclude that strong relationships in ecosystem processes and population dynamics can fluctuate in synchrony in fish populations in large marine ecosystems separated by thousands of kilometres. Previous studies have mainly focused on short-lived small pelagic species. Alheit and Bakun (2010) showed that the Benguela sardine varied in a multi-decadal synchrony with the Peruvian anchovy, and Roy and Reason (2001) suggested a similar oppositely-phased variability between sardines from the Canary current and Pacific sardine (*Sardina pilchardus*) populations. Our research found groupings of species that had common features that included benthic, semi-pelagic and bathydemersal life styles and had short and long life histories, at sub-basin, basin and multi-basin scales, further supporting the influence of large-scale physical-biological synchronies. Our study found three common recruitment trends, which were reflected within clusters (e.g. lings and hakes) and between clusters (e.g. grenadiers). The southern hemisphere ling stocks (*Genypterus blacodes*) share similar benthic-demersal habitat on the continental shelf and slope in New Zealand, Australia and Chile (Ward et al. 2001; Smith and Paulin 2003; Wiff et al. 2011). Broad-scale environmental variables may therefore be affecting recruitment processes across each of the wide-spread regions, leading to the groupings observed in this study. These trends were similar both within ocean basins (e.g. lings) and across multi-ocean basins (e.g. hakes and grenadiers). In contrast, stocks of toothfish were associated with different clusters and trends, suggesting greater impacts of the local environment on recruitment.

Some species did not show clear groupings (toothfish, jackass morwong, silver warehou). Results here suggest that in those cases, recruitment is driven in a different way to the apparent groupings. Additional work to include more species and other climate series may improve these results, and provide insights into the potential for environmental drivers to be influencing recruitment patterns for these stocks.

Consistency of the results from CA and DFA (Fig. 2.2) is encouraging, but some species with similar trend influences were clustered under different groups. An example is Australian blue grenadier, apparently more consistent with Trend 1, but grouped in C5 rather than C1. In addition, the DFA trends with the climate indices are an interesting result (Fig. 2.3). This suggests that the three selected climate indices may make a considerable contribution in explaining the main underlying trends in recruitment across a large number of species. While this may not be unexpected, our analysis does make progress in providing a demonstration of the possible broad-scale influence of the climate indices.

Large-scale climate indices have been correlated with sub-basin and basin scale recruitment patterns in the Northern Hemisphere species (Koslow 1984; Hollowed et al. 2001; Mantua et al. 1997). Here we found that similar indices that represent the Southern Hemisphere climate - IPO, SOI and SAM, explained part of the variation in several species, suggesting recruitment responses to large scale climate processes.

Dunn et al. (2009) found correlations between the strength of the first year class (YCS) and climate indices in an analysis of 20 climate indices and 212 YCS in New Zealand. However, because of the lack of consistent fits across different years for the same species they cautioned that these correlations could be spurious due to the uncertainty in YCS and recommended more robust statistical analysis. Dickey-Collas et al. (2014) also caution using recruitment data when it is derived from different models, especially when the data is noisy or sparse.

We used CA and DFA to determine common patterns in recruitment and were able to demonstrate the benefits and synergy in using these combined approaches. Zuur et al. (2003a) state that DFA can be a useful technique in the toolbox of a fisheries scientist and our results demonstrate the utility of DFA in identifying different trends in recruitment parameters. DFA has previously been used to identify common patterns in abundance (Ligas et al. 2011; Stachura et al. 2014), growth (Baudron et al. 2014), catch rate (Erzini et al. 2005) in the Northern Pacific (Stachura et al. 2014), Mediterranean (Ligas et al. 2011) and Northeast Atlantic (Zuur and Pierce 2004;

Erzini et al. 2005). However, Zuur et al. (2003a) caution about using DFA as a sole analytical technique. We combined DFA with CA and the similarities therefore provide a stronger case for the observed patterns within and across ocean basins. DFA has previously been used with Min/Max autocorrelation factor analysis (MAFA) (Erzini et al. 2005; Ligas et al. 2011) and Principal Component Analysis (PCA) (Stachura et al. 2014).

This work suggests that there are potential linkages in recruitment patterns at sub-basin, basin and multi-basin scales and that regional and global climate indices do account for some of the variation in some species. Although the climate indices examined here appear to explain a significant fraction of the observed variability for some species, it is likely that other physical and biological processes influence recruitment variability in Southern Hemisphere fish stocks. The building of larger global datasets, improved and standardized methods for obtaining recruitment data and the use of multiple analytical methods are likely to lead to greater future resolution of the drivers for recruitment variability and help our understanding of how climate and other environmental factors affect the productivity of fish stocks. In a global context, with ongoing environmental changes, the causes of recruitment variations need to be strategically considered in the development of management strategies to maintain sustainable utilisation of marine resources.

2.6 Acknowledgements

Funding for C.C-J. was provided by Becas Chile-scholarship (granted by CONICYT, Government of Chile) and CSIRO-UTAS QMS program. Australian Fisheries Management Authority (SESSF, Australia), R. M Hurst and A. McKenzie (NIWA), J.C Quiroz (IFOP), D. Butterworth and R. Rademeyer (MARAM, South Africa) and The Falkland Islands Government Fisheries Department have provided the data used in this study. B. Fulton, S. Curin, P. Thompson, C. Weldrick and two anonymous reviewers have helped to improve the manuscript.

Table 2.1. Stocks considered by country and the time period used for statistical analyses.

Name	Abbreviation	Data Source	Period
Tiger flathead	AUFLT	Australia, CSIRO	1980 - 2008
Deep-water flathead	AUFLD		1980 - 2007
Jackass morwong	AUMOW		1980 - 2005
School whiting	AUSHW		1980 - 2004
Gemfish (east)	AUGEME		1980 - 2008
Silver warehou	AUSIW		1980 - 2007
Pink ling (east)	AULIGE		1980 - 2009
Pink ling (west)	AULIGW		1980 - 2009
Blue grenadier	AUGRE		1980 - 2010
Blue warehou (west)	AUWARW		1980 - 2006
Blue warehou (east)	AUWARE		1980 - 2005
Toothfish (Macquarie Island)	AUTOF		1985 - 2003
Southern hake	NZHAK1	New Zealand, NIWA	1980 - 2008
Southern hake	NZHAK4		1980 - 2009
Southern hake	NZHAK7		1980 - 2010
Pink ling	NZLIG56		1980 - 2007
Pink ling	NZLIG34		1980 - 2007
Pink ling	NZLIG6B		1980 - 2006
Pink ling	NZLIG7		1980 - 2008
Blue grenadier (Hoki)	NZGRE		1980 - 2010
Toothfish (Campbell Island)	NZTOFC		1980 - 2010
Toothfish (Bounty Platform)	NZTOFB		1988 - 2010
Southern hake	CHHAK	Chile, IFOP	1980 - 2010
Patagonian toothfish	CHTOF		1989 - 2010
South Pacific hake	CHPHAK		1980 - 2010
Patagonian grenadier	CHGRE		1982 - 2010
Pink ling (South)	CHLIGS		1980 - 2010
Deep-water Cape hake	SADHAK	South Africa, MARAM	1985 - 2010
Shallow-water Cape hake	SASHAK		1985 - 2010
Patagonian toothfish	FITOF	Falkland I, FD	1986 - 2010

Table 2.2. AIC values obtained by applying DFA models using different covariance matrix (R) and number of trends (m) (K: number of parameters; AICc: second order Akaike index criteria, best model in bold text).

Model	R	m	logLik	K	AICc	delta.AICc
1a	diagonal and equal	1	-1110.71	31	2285.89	49.01
2a	diagonal and equal	2	-1065.63	60	2260.75	23.87
3a	**diagonal and equal**	**3**	**-1019.91**	**88**	**2236.88**	**0.00**
4a	diagonal and equal	4	-993.85	115	2254.92	18.04
5a	diagonal and equal	5	-969.89	141	2279.73	42.86
6a	diagonal and equal	6	-944.34	166	2303.93	67.05
1b	diagonal and unequal	1	-1100.97	60	2331.43	94.55
2b	diagonal and unequal	2	-1033.45	89	2266.47	29.59
3b	diagonal and unequal	3	-1000.50	117	2273.63	36.75
4b	diagonal and unequal	4	-947.21	144	2243.11	6.24
5b	diagonal and unequal	5	-910.11	170	2248.04	11.16
6b	diagonal and unequal	6	-879.14	195	2268.28	31.40
1c	equalvarcov	1	-1108.71	32	2284.07	47.19
2c	equalvarcov	2	-1061.31	61	2254.42	17.55
3c	equalvarcov	3	-1018.68	89	2236.91	0.04
4c	equalvarcov	4	-993.69	116	2257.28	20.40
5c	equalvarcov	5	-969.67	142	2282.19	45.31
6c	equalvarcov	6	-945.23	167	2308.84	71.96

Table 2.3. Significance of Pearson correlations of recruitment deviation, DFA trends and climate indices from 1980 to 2010 (grey correlation p-value < 0.1, bold correlations p-value < 0.05).

	AUFLT	AUFLD	AUMOW	AUSHW	AUGEME	AUSIW	AULIGE	AULIGW	AUGRE	AUWARW	AUWARE
IPO	0.14	-0.03	**0.48**	**-0.46**	-0.01	-0.07	0.04	0.03	**0.39**	0.14	0.19
SAM	0.27	-0.14	-0.17	0.26	-0.19	0.34	-0.08	-0.03	-0.06	-0.18	-0.28
SOI	-0.21	0.02	**-0.5**	0.37	-0.02	-0.01	-0.25	-0.28	-0.26	-0.17	-0.03

	AUTOF	NZHAK1	NZHAK4	NZHAK7	NZLIG56	NZLIG34	NZLIG6B	NZLIG7	NZGRE	NZTOFC	NZTOFB
IPO	0.03	-0.02	-0.02	0.08	-0.08	-0.03	0.31	0.14	**0.5**	-0.15	0.05
SAM	**0.49**	-0.04	-0.31	-0.28	0.19	0.05	**-0.43**	-0.36	**-0.48**	-0.21	-0.4
SOI	0.02	-0.01	0.19	-0.07	0.04	0.08	-0.25	0.08	**-0.44**	-0.02	-0.16

	CHHAK	CHTOF	CHPHAK	CHGRE	CHLIGS	SADHAK	SASHAK	FITOF	TREND1	TREND2	TREND3
IPO	0	0.08	0.16	**0.44**	0.09	0.13	0.33	**0.44**	**-0.41**	-0.09	0.02
SAM	-0.24	0.29	0.09	0.17	0.28	-0.02	-0.05	-0.2	0.31	-0.18	0.04
SOI	-0.14	0.3	**-0.36**	-0.23	-0.2	-0.25	0.02	-0.31	0.25	0.10	-0.32

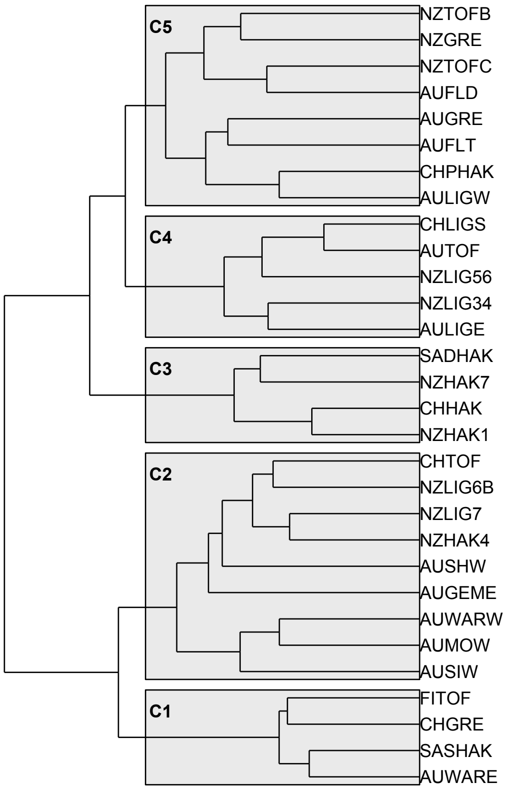


Fig. 2.1. Cluster analysis using annual recruitment residuals in all years separated by groups (C1, C2, C3, C4 and C5).

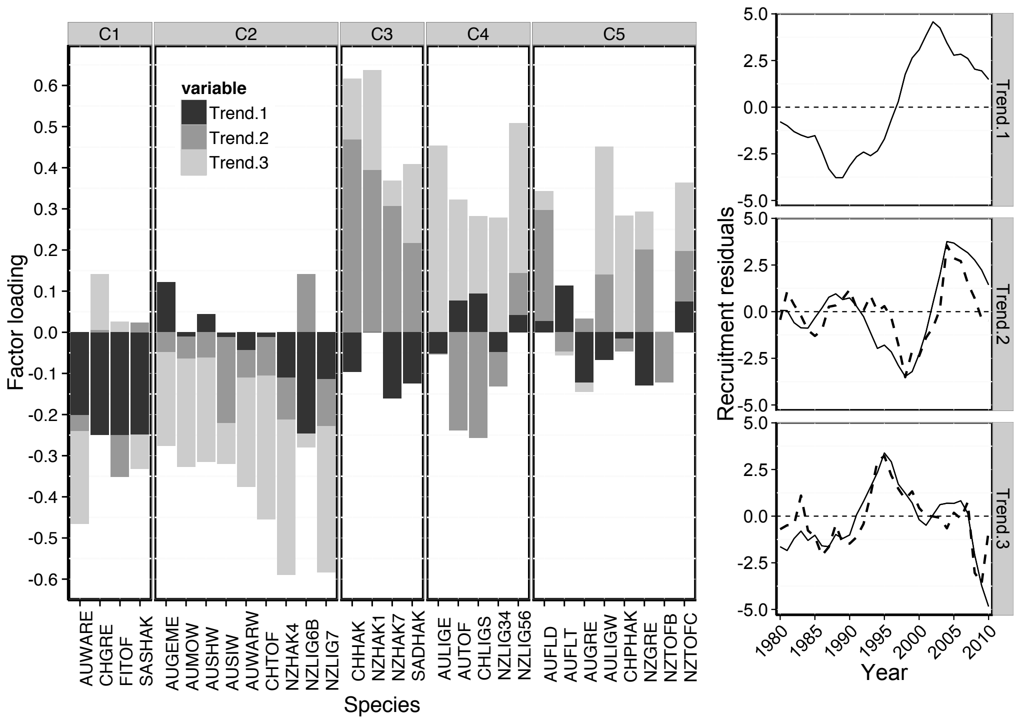


Fig. 2.2. Factor loading of the 5 clusters determined from the cluster analysis (left) and common trends (right) in the DFA analysis. Cluster 3 and Cluster 4 averages (dash line) of recruitment residuals and weightings are presented for Trend 2 and Trend 3 respectively.

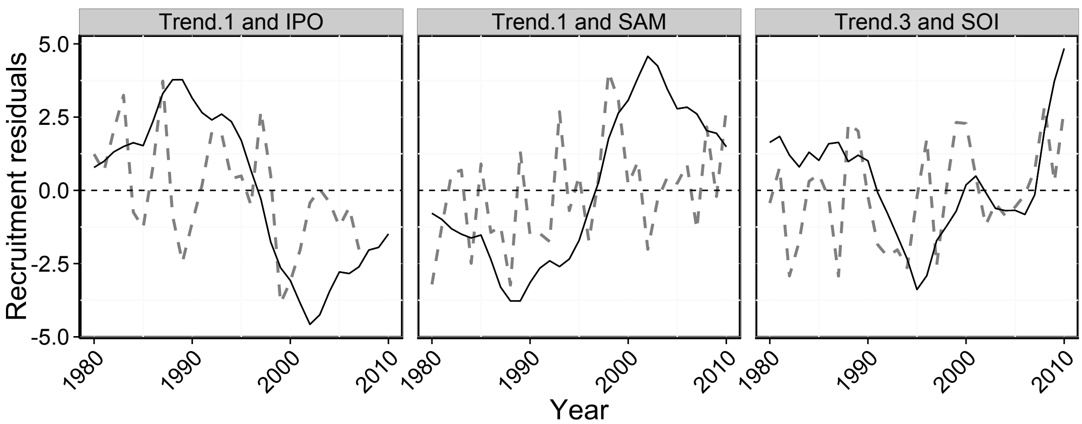


Fig. 2.3. DFA trends (black line) and climate indices (dash line) following the correlations described in Table 2.3. We have inverted Trend 1 (left) and Trend 3 (right).

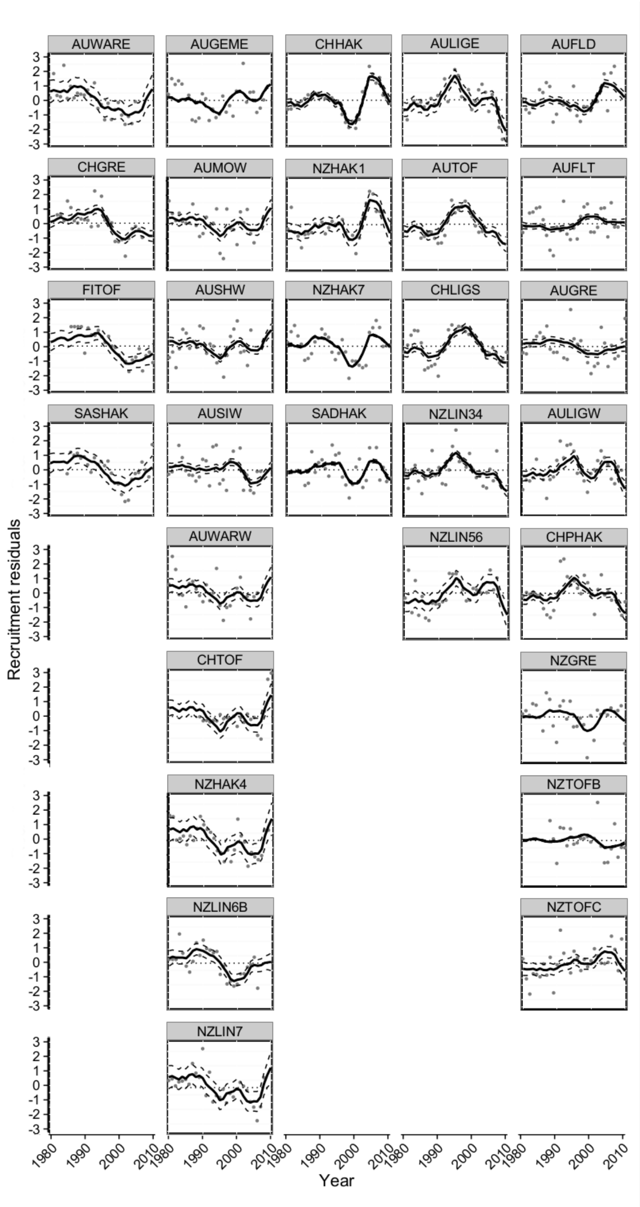


Fig. 2.4. Standardized recruitment deviation time series of stocks considered in the analysis (filled circles), along with the fitted values including 95 % confidence intervals (dash lines) from the selected DFA model (line) following the same order (in columns) as cluster analysis (from Cluster 1 (left side) to Cluster 5 (right side)).

Chapter 3

3 STOCK ASSESSMENT FOR PATAGONIAN GRENADIER (*Macruronus magellanicus*) USING STOCK SYNTHESIS

3.1 Abstract

Patagonian grenadier (*Macruronus magellanicus*) is one of the main commercial fish of the demersal and mid water fisheries of Chile. Landings in Chile reached a maximum of 370,000 tons in the 1990s, before declining to 40,000 over the last few years. Fish stock assessments support the management of fisheries resources by describing fish stock status and providing estimates of key quantities of interest, such as temporal trajectories of spawning biomass, under different biological and management scenarios. The Patagonian grenadier stock assessment model developed in this chapter is a Stock Synthesis model using data from 1985 to 2013. Stock Synthesis is a statistical age-structured population modeling framework. The Stock Synthesis assessment for the species suggests a recent decline in abundance off the Chilean coast. Age and length data from fleets, integrated within the Stock Synthesis model suggests that the stock-recruitment relationship changed significantly after 1999, affecting stock productivity. The Chilean Patagonian grenadier stock appears to be in a critical situation, with biomass levels that are severely depleted. The current poor status of this stock has consequences across the fisheries sector. Rebuilding the stock is the next challenge for all the stakeholders involved in this fishery. Here I provide a Stock Synthesis assessment of the stock status of Patagonian grenadier and provide potential future catches under differing stock structure scenarios. To account for the observed marked decline in recruitment since 1999, I also include an

alternative assessment model that allows a shift in recruitment productivity. This change in model structure has profound implications for the interpretation of stock status and recommended catch levels.

3.2 Introduction

The family Merluccidae is part of the gadoid group, which is divided into two subfamilies: *Merlucciinae* and *Macruroninae* (Lloris et al. 2005). The genus *Macruronus* has a limited distribution within the Southern Hemisphere. The total annual *Macruronus* landings across all fisheries reported at the end of 20th century was 700,000 tonnes (FAO 2005 cited in Lloris et al. 2005). In Chile, Patagonian grenadier is the second most important demersal species, with landings around 40,000 t in 2014. It is divided into two species; blue grenadier or hoki (*Macruronus novaezelandiae novaezelandiae*) and Patagonian grenadier (*Macruronus novaezelandiae magellanicus*). The common names for this species are blue grenadier (Australia), hoki (New Zealand), Patagonian grenadier (Chile) and Patagonian hoki (Argentina and the Falkland Island).

Patagonian grenadier is the most abundant gadoid resource in Chilean Patagonia (41º40' to 52ºS) (Tascheri et al. 2010) and is also an important resource for Argentina (Ministerio de Agricultura, 2012) and the Falkland Islands (Falkland Islands Government, 2013). The species occurs in two geographical areas: the Southeast Pacific between Valparaíso (33º S) and Cape Horn (55º 58' S) in Chile (Arana 1970 cited in Prenski et al. 2012), and in Argentina in the Southwest Atlantic between 33º S and 57º S (Wölhler and Giussi 2001 cited in Schuchert et al. 2010). In Chile, Patagonian grenadier has shown a decline in biomass in recent years (Paya and Canales 2011). According to Paya and Canales (2011), the stock assessment estimated a decline in biomass starting in 2004, and was preceded by a considerable reduction in recruitment from 1999. This reduction has been correlated with a shift to colder sea surface temperatures in the main spawning/nursery areas of the species (Cubillos et al. 2014).

Stock assessments use statistical and mathematical methods to predict temporal trajectories of the historical state of marine populations and the likely response of these populations to alternative plausible management preferences (Hilborn and Walters 1992). Fisheries stock assessments support the management of fisheries resources, describing fish life states, possible results under different management scenarios, and can estimate the probability of different fisheries states under different management approaches and policies (Hilborn 2003). Assessments, such as the integrated assessment described in this chapter, integrate different data sources (e.g. catch, age composition, abundance index (see Fig. 3.2) into a single analysis with a joint likelihood for the observed data (Maunder and Punt 2013).
The previous model developed for the Chilean Patagonian grenadier stock assessment was led by the Chilean fisheries institute (IFOP) and developed by Chilean researchers (Payá 2014) and international collaborators (Quinn and Cox 2011). The assessment used an age-structured model programmed in AD Model Builder (Fournier et al. 2012). In this chapter I follow a similar structure using the population modeling framework Stock Synthesis (version 3.24U; Methot, 2011), by including the data used by IFOP in its assessment. In addition, I have incorporated the main recommendations given to IFOP by the peer review panel such as the omission of the

years in the trawler CPUE where the Patagonian grenadier was changing from bycatch (not targeted) to target specie, and to not use the purse seine CPUE index since it is contradictory with the reality (Quinn and Cox 2011).

Stock Synthesis can include complex dynamics and incorporate different data sources as well as biological and environmental processes into the stock assessment model (Methot and Wetzel, 2013). Stock Synthesis models have been applied to 12 stocks of the Southern and Eastern Scalefish and Shark Fishery (SESSF) in Australia (Tuck 2012), 35 stocks in the US, 10 large pelagic fisheries in three oceans and four European fish stocks. This shows the flexibility and global acceptance of Stock Synthesis for fish stock assessment and management (Methot and Wetzel 2013).

Environmental change, including the direct effects of climate change, can increase the uncertainty of the dynamics of fish populations and their associated fisheries. Given that fish may have large dynamic response to climate variation, stock assessments should consider environmental variables as part of the traditional modelling and assessment frameworks (A'mar et al. 2009). Regime shifts and long-term changes in climate and/or the dynamics of climate variation may create instability in biological characteristics such as growth and mortality rates, the frequency of high and low recruitment events, changes in stock distributions, and changes in stock-recruitment relationships. Hollowed et al. (2008) show a framework for modelling fish responses that includes climate change variables. Specifically, Hallowed et al. (2008) highlighted that models need to add environmental variables to assessment models so that they capture greater realism to modelled scenarios and prediction. Such environmentally adjusted models were considered to incorporate a greater level of conservatism to account for the uncertainty of climate change impacts.

A review of methods to incorporate regime shifts in stock assessment and management of marine resources has been developed by King and McFarlane (2006). These authors identify the difficulties and propose potential frameworks that incorporate regime shifts into management and assessment.

The main goals of this chapter are to develop a Stock Synthesis model to assess the Patagonian grenadier fishery in Chile and begin an exploration of whether to include a potential shift in recruitment productivity. Validation of the Stock Synthesis model was undertaken by comparing outputs with the previous assessment model by IFOP. The models can then be compared for their relative ability to fit the observed data and their consequent predictions of stock status and yield. I use the Stock Synthesis modelling approach to assess the Chilean stock of Patagonian grenadier using catch at age data, catch landings, acoustic surveys, size at maturity and catch per unit effort data. This is the first stock assessment using this model for Chilean Patagonian grenadier and the first to also consider a recruitment shift in the stock dynamics.

3.3 Material and methods

3.3.1 The data and model input

To validate the Stock Synthesis model, I compared the outputs of the Stock Synthesis model with the existing IFOP model. It was essential that the same input data were used in both models.

3.3.1.1 Biological parameters

A single sex model (sex ratio of 0.5) was used, as the age, survey and length composition data for Patagonian grenadier are not available by sex. The biological parameters are outlined in Table 3.1, using the parameters reported by Chong et al. (2007) for Patagonian grenadier in Chile and assuming a von Bertalanffy function for growth.

Table 3.1. The fixed biological parameters used for the Patagonian grenadier stock assessment.

Parameters	Value
Growth K	0.176
Growth L_{max} (cm)	103.5
Natural mortality (M)	0.35
Steepness (h)	0.75
Recruitment residual σ_R	0.68
Length-weight scale, a	3.38 10^{-6}
Length-weight power, b	2.96
Length at 50% maturity (cm)	54
Maturity slope	-6

3.3.1.2 Fleets

The base case assessment for Patagonian grenadier is configured to have four fleets, with time varying selectivity estimated separately for each fleet. The fleets are:

- Purse seine (Centre of Chile, Patagonian grenadier is the target species)
- Trawler South 1 (South of Chile, Patagonian grenadier is not target species)
- Trawler South 2 (South of Chile, Patagonian grenadier is the target species)
- Trawler Centre (Centre of Chile, Patagonian grenadier is the target species)

This assessment does not consider discard mortality, as discarding of fish is assumed to be negligible (Payá 2014).

3.3.1.3 Catches

The model uses a calendar year for all catch data. The comparatively negligible landings recorded prior to 1985 are not considered in this assessment (Payá 2014). Catches were considered from 1985 to 2014. Annual landed catches by fleet used in this assessment are shown in Figure 3.1.

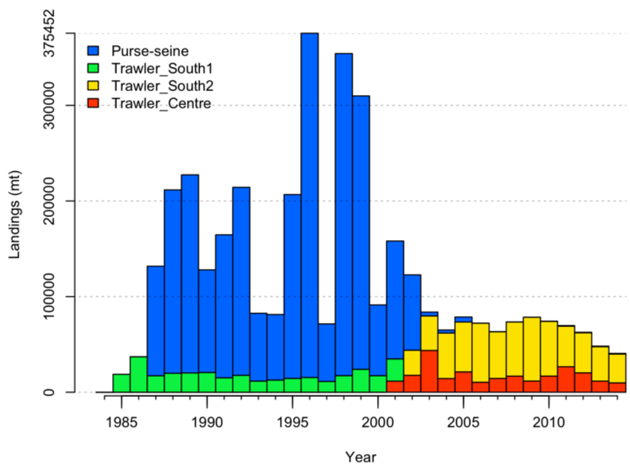


Fig. 3.1. Total landed catch by fleet of Patagonian grenadier from 1985 to 2014 as used in this assessment.

3.3.1.4 Catch rate indices

Standardized catch per unit effort (CPUE) for Patagonian grenadier data (Paya, 2014) are available from the period 1985 to 1996 for Trawler South 1, and from 2002 to 2013 for Trawler South 2. To compare across these different fleets, catch rates were standardized by Payá (2014) using GLMs following the methodology presented by Tascheri et al. (2010). Temporal changes in selectivity have followed the recommendations (Payá and Canales 2011) used by IFOP in the Chilean Patagonian grenadier stock assessment in 2014.

The selectivity of the trawl fishery and the acoustic survey was modeled using two curves for two periods. Dome-shaped selectivity was used to describe the exploitation pattern for the Trawler South 1 fleet for all periods. The Trawler South 2, Trawler Centre and the acoustic survey fleet were divided in two periods with different logistic selectivity parameters, since the populations are markedly showing smaller fish since 2008. This follows the fleet selectivity structure of IFOP described in Payá et al. (2014).

3.3.1.5 Fish length and age composition data

The length frequency and age composition data were obtained from the historical records collected by IFOP from different fisheries programs. These age frequencies have been composed from periodic sampling from catch and fishery independent surveys. The data were then transformed to age using an age-length key generated from otolith readings. The age-length matrix is formed by catch at age data (1 to 14+ ages) for the main fleets. Length data (20 to 80 cm) is only available for the purse seine fleet and for 1988 and 1996.

3.3.1.6 Fishery Independent Survey estimates

Abundance indices include acoustic biomass estimates and age composition from the acoustic survey from 2000 to 2013 (data included in the Appendix 3). Payá (2014) documented details of the data used for the stock assessment, as well as the survey's methodological aspects. Catchability is configured to be 1.0 for these surveys.

3.3.1.7 Input data summary

The temporal scope of data used in this assessment is summarized in Figure 3.2, indicating which years the various data types were available.

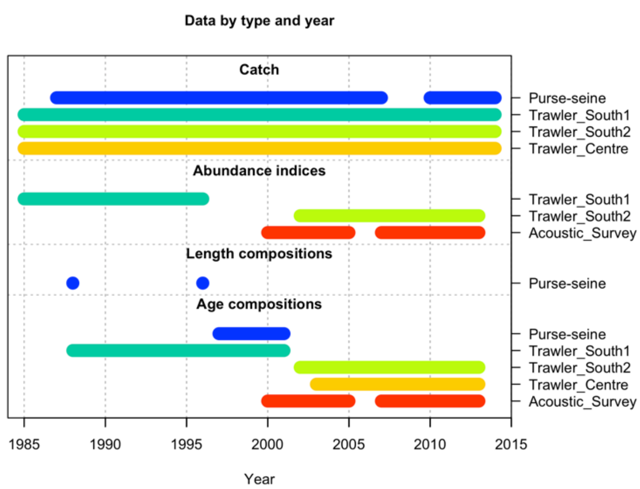


Fig. 3.2. Summary of input data used for the Patagonian grenadier assessment.

3.3.2 Stock assessment method

3.3.2.1 Population dynamics model and parameter estimation for the base case model.

A stock assessment for Patagonian grenadier was conducted using a statistical age and length-structured model implemented in the age-structured population modeling framework Stock Synthesis (version 3.24U; Methot, 2011), and included age data from 1985 to the end of 2014. In addition, this stock assessment includes implementation of the tuning method described in Day (2016). The population dynamics model and the statistical approach used in fitting the model to the various types of data are specified in Methot and Wetzel (2013).

The rate of natural mortality (*M*) is set to 0.35 yr^{-1} (Chong et al. 2007) and is configured to be age- and time-invariant (Payá 2014; Punt et al. 1994; Punt et al. 2001b; Tuck 2012; Whitten et al. 2013). The parameters of the von Bertalanffy growth function (K and L_{max}) are obtained from Chong et al. (2007). A plus group is modeled at age 15, and maturity is modeled as a logistic function with 50% maturity at 57 cm (Chong et al. 2007). The estimated parameters from the base case model are: average recruitment at unfished equilibrium spawning biomass (calculated at the start of the fishery in 1985) recruitment deviations from 1985 to 2012, stock recruitment curve parameters, and selectivity parameters. The true annual recruitment variability is a key factor to predict the range of fluctuation in the future that will depend on the actual variability and not the variability produced by the imperfection of the historical data (Maunder and Deriso 2003). The bias adjustment method adjusts the recruitment estimates to be mean unbiased penalizing the likelihood method including a time-varying correction (Methot and Taylor 2011).

The parameter values are estimated by fitting to catches, catch rates, survey indices, catch at age frequency, and survey age frequency data. Outputs have been summarised and plotted using the R package R4SS (Taylor et al. 2014), a library developed to show Stock Synthesis results. Since I am using different data sources (e.g. age and growth, catch, catch at age, abundance index) it is necessary to balance the weighting of each of the data sources that contribute to the overall likelihood function (Francis 2017; Punt 2017). The more challenging part is to give appropriate weights for compositional data (length-compositions and age composition data). Here I have used the McAllister-Ianelli-2 method to determine the weights for the length and age composition data (McAllister and Ianelli 1997; Francis 2011; Day 2016).

3.3.2.2 Sensitivity tests

For the sensitivity tests, two main model structures are considered. The first is a model that follows the features proposed by IFOP in Chile (Payá et al. 2014). This model is referred to as the No-Shift model (base case) as it does not include an environmental link parameter (ρ_{env}) (recruitment shift parameter). The second is a model that is similar to the previous one, but it allows two distinct recruitment periods with differing relative productivity of the stock. This is achieved through estimating two values of the average recruitment at unfished equilibrium (R_0) – one at the start of the fishery in 1985, and one at the start of the lower recruitment regime in 1998. This model is referred to as the Shift model. The Shift model include the following equations to adjust the level of recruitment:

$$\check{R}_t = f(SSB_t) \times \exp{(\beta \, E_t)},$$

where β is the slope parameter relating the environmental time-series (E_t) to the recruitment deviation. Total recruitment was given by:

$$R_t = \check{R}_t \exp(-0.5\sigma_R^2) \exp{(\check{R}_t)},$$

where σ_R is the standard deviation for recruitment in log space.

The ρ_{env} parameter creates a multiplicative adjustment to the target parameter, in this case as follow:

$$R_t = R \exp{(\rho_{env} \, E_t)}$$

Different tests were used to check the sensitivity of results to the two model structures.

1. Shift: regime shift occurred in 1998. This model considers two stock recruitment levels;
2. Steepness h = 0.9 (0.75 in the base case);
3. Half (05survey) and double (2survey) the weighting on the acoustic survey data;
4. Estimation of growth parameters (VB)
5. Half (05age) and double (2age) the weighting on the age composition data;
6. Double (05survey) and half (2survey) the weighting on the acoustic survey data;
7. Natural mortality M = 0.2 yr^{-1} and 0.5 yr^{-1} (0.35 base case);

The sensitivity test results are summarized by the following quantities:

1. $SSBo$ the average equilibrium spawning biomass
2. SSB_{2015} the spawning biomass at the start of 2015
3. SSB_{2015}/ SSB_o the depletion level at the start of 2015
4. 2015 Recommended Biological Catch (RBC). The 2015 RBC, calculated using the 20: 35: 48 harvest rule (B_{lim}: B_{MSY}: B_{targ})
5. Long term RBC. The long-term RBC calculated using the 20: 35: 48 harvest rule.
6. –lnL is the negative of the logarithm of the likelihood function. The lnL's are used to compare the performance of models of the same structure that use different datasets.

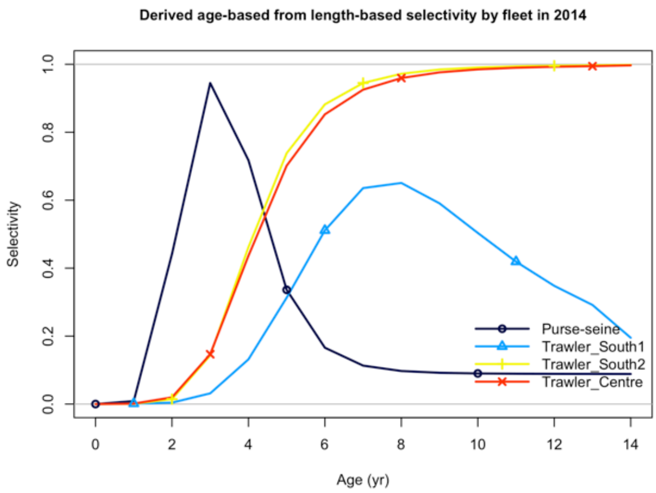
For this assessment of the Patagonian grenadier fishery I used a harvest strategy framework (HSF) similar to that implemented for Tier 1 fisheries in the Southern and Eastern Scalefish and Shark Fishery (SESSF) in Australia (Smith et al. 2008) and it will be used as a basis to provide TAC advice for the projected years. The HSF uses harvest control rules to establish a recommended biological catch (RBC) for the Patagonian grenadier fishery. This rule includes a 20: 35: 48 strategy (B_{lim}: B_{MSY}: B_{targ}). B_{lim} is the limit biomass that represents the spawning biomass level below which the stock is considered to be overfished. It is 20% of the unfished spawning biomass. B_{MSY} represents the spawning biomass level which would result in a maximum sustainable yield (MSY). B_{targ} is the spawning biomass level which is equal to the biomass at the maximum economic yield (MEY). Following Smith et al (2008), this value is assumed equal to 1.2 * B_{MSY} or $B_{48\%}$ of the unfished spawning biomass if it is assumed that B_{MSY} corresponds to the biomass at 35% depletion.

3.4 Results

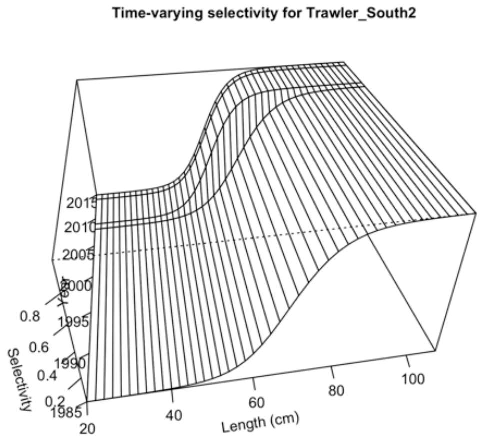
3.4.1 Parameter estimates of the No-Shift model (Base case)

Figure 3.3 shows the estimated variation in selectivity curves for all trawl fleets, the purse seine fleet and the acoustic survey for Patagonian grenadier from 1985 to 2014. A major shift in selectivity occurs in 2009 for the Trawler South2 and the acoustic survey. The parameters that define the selectivity functions include the length at 50% selection and the variance. The estimates of these parameters for the base-case analysis are 45.63cm for purse-seine, 87.90cm for Trawler South1 (1985 to 2001), 60.37cm for Trawler South2 (2001 to 2008), 61.07cm for Trawler Centre (2003 to 2013) and 48.11cm for the acoustic survey (2000 to 2007). The estimates for the parameters after the shift in selectivity for the period 2009-2014 are 68.84cm and 16.71cm respectively for the Trawler South2 and 64.45cm and 17.56cm for the acoustic survey. The estimate of the parameter that defines the initial numbers (and biomass), $ln(R_0)$, is 14.231 for the base case.

(a)



(b)



(c)

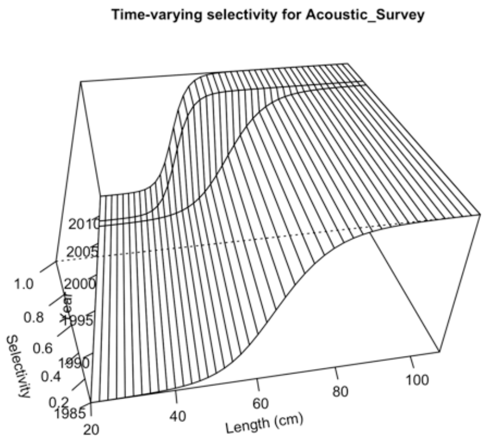


Fig. 3.3. Selectivity profiles for the different fleets (a) as a function of age. Length and time selectivity response for the acoustic survey and Trawler South 2 from 1985 to 2008 are presented in (b) and (c) respectively.

3.4.2 Fits to the data for the No-Shift model

The fits to the catch rate indices for the trawler south 1, trawler south 2 and the acoustic survey fleet are shown in Figure 3.4. The model fits include the 95% confidence intervals for the data analysed. Trawler South 1 estimation is relatively flat, but still between the confidence intervals. Trawler South 2 and the acoustic survey fit show the reduction of the abundance index and follow the observed CPUE trend correctly during the period analyzed. Fits to the biomass estimates from the acoustic survey and CPUE index were reasonable.

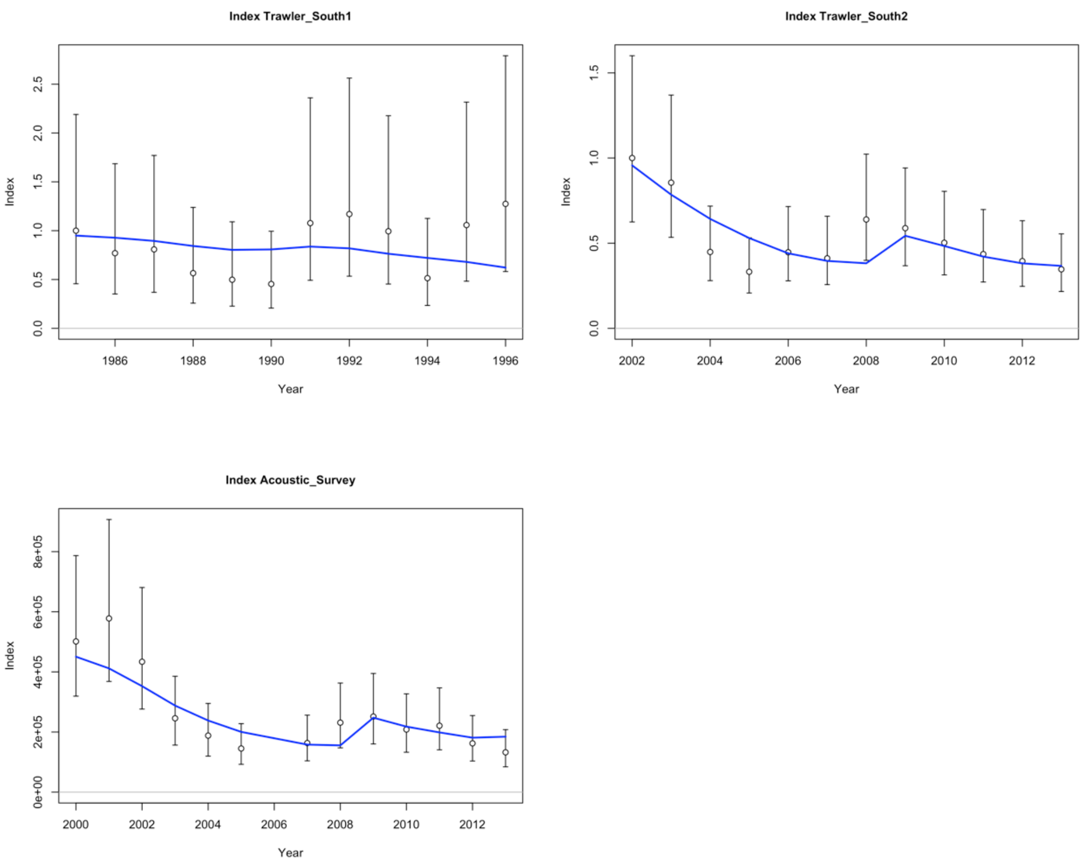


Fig. 3.4. Observed (circles) and model predicted (blue line) catch rates for Patagonian grenadier for the two southern trawl fleets and the acoustic biomass survey. The vertical lines indicate 95% confidence intervals for the data.

The model can replicate the aggregated age composition data reasonably well (Fig. 3.5) showing similar catch per age in the trawl fleet and acoustic survey, and catching younger aged fish in the purse-seine fleet. Annual fits and residuals of the age composition are included in the Appendix 1.

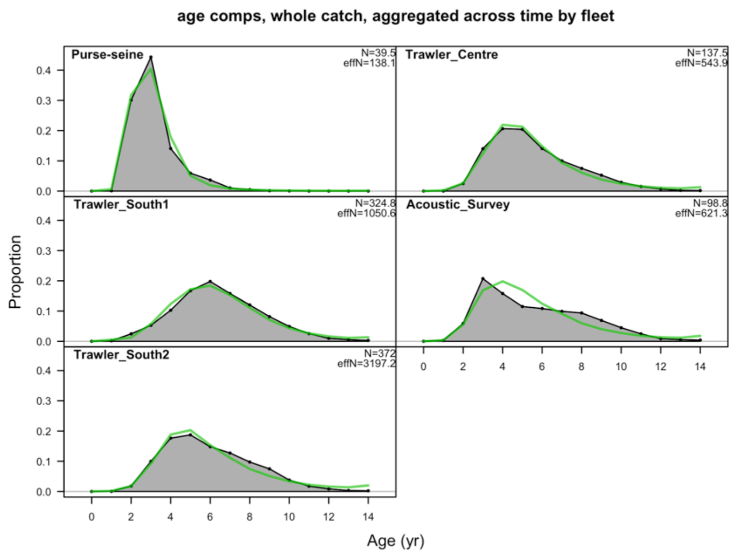


Fig. 3.5. Aggregated age composition data for all fleets and the acoustic survey. Observed data are grey and the fitted value is the green line.

3.4.3 Assessment outcomes for the No-Shift model

The spawning biomass shows a large decline in 1998 (Fig. 3.6), changing the trajectory and the production of the spawning biomass and recruitment. The stock recruitment curve in the No-Shift model shows higher recruitment at the beginning of the time series with values over 1.5 million recruits. The No-Shift model considers the average of the stock recruitment curve during the whole assessment period. The bias adjustment and recruitment deviation estimates are shown in Figure 3.7. On the other hand, the Shift model has two periods for the stock recruitment curve: a high recruitment period from 1985 to 1997, and a low period from 1998-2014.

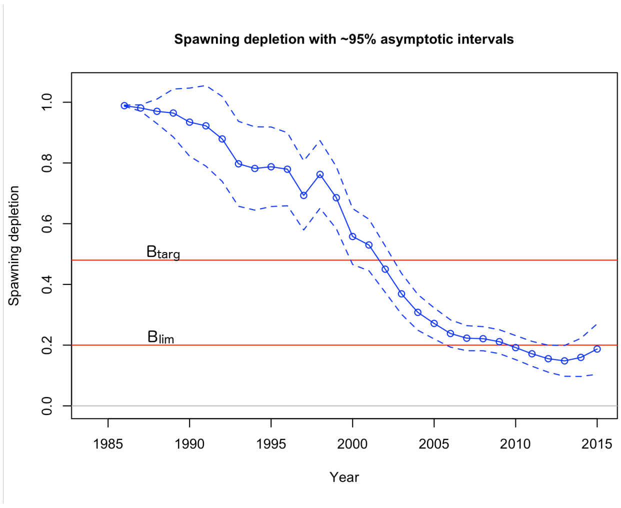


Fig. 3.6. Time-trajectory of spawning biomass depletion (including 95% confidence intervals) corresponding to the estimates for Patagonian grenadier for the base case No-Shift model. (The horizontal red lines show B_{lim} and B_{targ}).

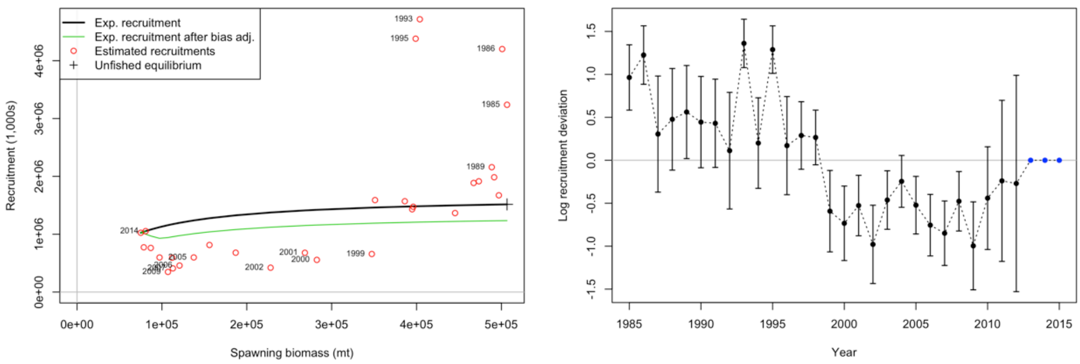


Fig. 3.7. Recruitment estimates for the base case (No-Shift model) for Patagonian grenadier and estimated log recruitment deviations.

Table 3.2. Summary of fixed and estimated parameters for the No-Shift model (base case).

Parameters	Details	
Growth K	fixed	0.176
Growth l_{max} (cm)	fixed	103.5
Natural mortality (M)	fixed	0.35
Steepness (h)	fixed	0.75
Recruitment residual σ_R	fixed	0.68
Length-weight scale, a	fixed	$3.38\ 10^{-6}$
Length-weight power, b	fixed	2.96
Length at 50% maturity (cm)	fixed	54
Maturity slope	fixed	-6
Recruitment deviations	estimated	1985-2013
$ln(R_o)$	estimated	14.231

3.4.4 Sensitivity tests

Results of the sensitivity test are presented in Table 3.3. Due to the marked pattern of higher followed by lower production from approximately 1999 seen in Figure 3.7, and the improved fit to the data, the key sensitivity for consideration from here onward is the Shift model. The Shift model shows a better fit of the recruitment curve to the magnitude of estimated annual recruitments (Fig. 3.8), as the model now has two stock recruitment relationships. In addition, the Shift model provides lower recruitment deviations from the re-estimated S-R relationship (red triangles compared to blue circles, Fig. 3.8). The environmental link parameter is estimated to be ρ_{env}=

1.186, and this produces the observed step in the stock recruitment curve (Fig. 3.8), unlike the No-Shift model (Fig. 3.7).

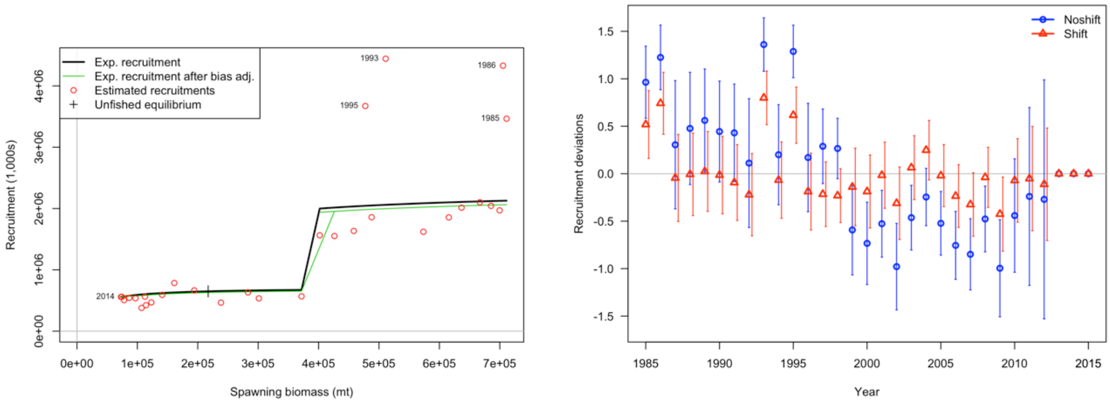


Fig. 3.8. Recruitment estimates for the Shift model for Patagonian grenadier (left) and time trajectories of estimated log recruitment deviations for the No-Shift (blue) and Shift model (red) (right).

The results show small differences in likelihood between the models across steepness and survey penalties. If the scenario includes less importance on the age composition, the likelihood is lower than all the other models. However, it does not look logical since the majority of the data is coming from the age composition data set. In addition, a high value for natural mortality gives good model performance, but its value was considered too high for a demersal species with a maximum age of 15 years.

Table 3.3. Summary of results for the base case and sensitivity tests (-log-likelihood (Likelihood) values. Spawning stock biomass includes both male and female biomass in the total. (*SSBo* No-Shift corresponds to *Bo* in 1985, and Shift corresponds to *Bo* in 1999) (RBC: Recommended Biological Catch).

N	Scenario	SSBo	SSB2015	SSB2015/SSBo	RBC	long term RBC	Likelihood
1	No-Shift	1013210	189646	0.19	5	131309	93.59
2	No-Shift h09	928525	166936	0.39	50346	135203	104.77
3	No-Shift 05survey	1078020	237250	0.22	9131	140414	102.67
4	No-Shift 2 survey	961623	159855	0.17	4	124032	72.43
5	No-Shift VB	891908	204265	0.23	11848	127491	85.82
6	No-Shift 05age	972110	176752	0.18	5	125599	57.11
7	No-Shift 2age	979985	178142	0.18	5	127796	194.29
8	No-Shift M02	1450640	75721	0.05	0.3	95646	136.21
9	No-Shift M05	1250890	516385	0.41	223121	261647	76.69
10	Shift	434423	158333	0.36	42867	56374	105.14
11	Shift h09	425235	198433	0.21	5815	61670	104.57
12	Shift 05 survey	430532	162626	0.38	44232	56158	113.49
13	Shift 2 survey	439076	154075	0.35	41495	56692	75.22
14	Shift VB	446226	163829	0.37	41679	54601	92.92
15	Shift 05age	439503	167140	0.38	45037	56742	44.65
16	Shift 2age	426670	155373	0.36	42205	55689	184.25
17	Shift M02	850067	96544	0.11	1	58051	142.83
18	Shift M05	462745	306401	0.66	135598	96208	68.05

The Shift models estimates two *Ro* values: one at the start of the assessment in 1985, and one at the beginning of the lower recruitment shift (1999). For the model using the recruitment shift, the current depletion is calculated by comparing spawning stock biomass in 2015 with an estimate of equilibrium spawning stock biomass for the regime starting in 1999, rather than unfished equilibrium stock biomass in 1985 as in the No-Shift model (Fig. 3.9). The No-Shift model shows a relative spawning biomass with small error during the analyzed period, but with a relative spawning biomass level under 20% indicating that the stock has been overfished since 2010.

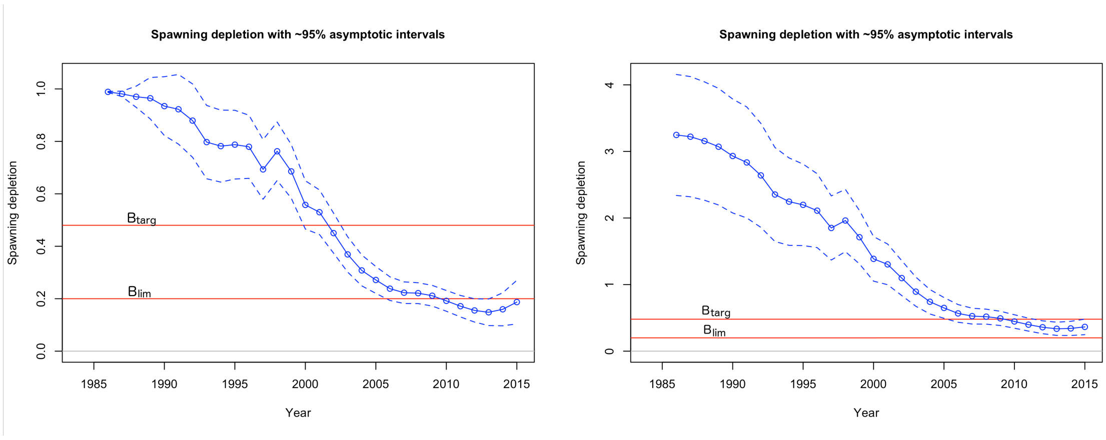


Fig. 3.9. Time-trajectory of spawning biomass depletion (with 95% confidence interval) for the No-Shift (left) and Shift (right) models. (The horizontal red lines show B_{lim} and B_{targ}).

The recruitment number at age zero (Fig. 3.10) show similar trajectories for each of the Shift and No-Shift models, with some differences after 2010. These latter values have limited data as catch and catch rate data is available but not otolith readings to determine age. This is reflected in the broader 95% confidence limits for these later years.

The No-Shift model (blue line) will predict higher average recruitment as it assumes a more productive stock through the estimated stock-recruitment curve based on the higher recruitments obtained prior to 1999.

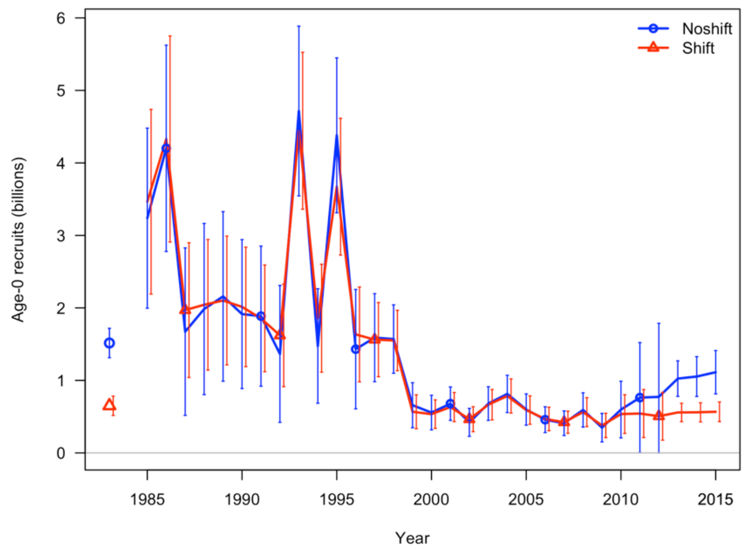


Fig. 3.10. The estimated recruitment number at age zero for the base case No-Shift (Blue) and Shift model (red). Blue circles correspond to R_{85} and red triangle R_{99}.

3.5 Discussion

In this chapter I developed a Stock Synthesis model for the Patagonian grenadier base on the parameters used for previous assessments of this species. The Stock Synthesis modeling platform offers the user the capability to analyse different data scenarios within a single framework. Methot and Wetzel (2013) highlighted this feature, mentioning its flexibility and that the software can simultaneously account for statistical catch-age analysis, and age-structured, biomass dynamics models and catch curve analysis. Fitting of the Stock Synthesis model provided similar results to previous assessments models and sensitivity analysis showed that the model has a stable performance. Patagonian grenadier age-structured data from the commercial catch and the acoustic survey are consistent, showing the stock with younger fish and a considerable decrease in catch of adult fish. The slope of the stock-recruitment relationship appears to have changed significantly since 1999, with a consequent effect on stock production, suggesting a possible regime shift (Fig. 3.8). The Patagonian grenadier fishery shows a change in recruitment in 1998 and by using the Stock Synthesis model I can incorporate a recruitment environmental link parameter. The Patagonian grenadier stock assessment performed with Stock Synthesis can now be a useful tool to compare results across different scenarios, such as those already considered by the Chilean government. Wayte (2013) evaluated a similar situation for jackass morwong (*Nemadactylus macropterus*) stock assessment in Australia. Jackass morwong stock status is now calculated by comparing current biomass with equilibrium biomass in 1988 and future recruitment estimates are based on a less productive stock recruitment curve.

The use of a standardised assessment framework that can be applied to any fishery can improve efficiency, as communication between researchers working on different fisheries across countries can provide support for other users, thus reducing the time required for debugging and processing and allowing the researcher to focus on the assessment results, rather than new code or programing issues.

Cubillos et al. (2014) explored this scenario, identifying a temperature regime shift as the most likely cause for the change in production. It is the first time that a recruitment shift has been suggested as a possible driver for the declining performance of the fishery and a link between the change in stock production and environmental change. Stock Synthesis gives the option to incorporate a recruitment-environment link to explore a recruitment shift scenario (Wayte 2013). I have incorporated this scenario that includes a recruitment shift from 1998, fitting the stock-recruitment curve with two periods. This considerably changed the stock-recruitment curve and recruitment deviations.

According to our results for the No-Shift assessment, the Chilean Patagonian grenadier stock is in a critical situation. The RBC level for the fishery has been set at 5 tonnes (Table 3.3) under the biological limit reference point set at 22.5% of *SBo* by the scientific committee (Subpesca 2016). For Australia and New Zealand grenadiers' fishery, the biological reference point is set at 20% of *SBo*. The New Zealand fishery has shown positive rebuilding after implementation of the harvest strategy (Livingston and Sullivan 2007) The 2012 stock assessment confirmed that the hoki stock has increased toward stock target levels (Livingston et al. 2015). Alternatively, the Shift model gives a current depletion above the limit reference point, but will also estimate a lower long term catch, as the stock is assumed to be less productive than in the past (see Chapter 4).

The purse seine fishery that was operating on a pulse of juveniles in the BioBio region (Latitude 37 South) was a seasonal fishery, and in 1996 and 1998 reaching historic levels over 300,000 tonnes of Patagonian grenadier during spring upwelling events where the stock was easily accessible and thus vulnerable to overexploitation of juveniles (Cubillos et al 2009). It is important to consider the potential overestimation of stock size and also recognize that recruitment overfishing are both a possible explanation for the observed marked decline in biomass. However, estimated TACs for Patagonian grenadier since 2009 have never been realised (Fig. 4.6, Chapter 4) and current landings are approximately 40,000 tonnes and show no signs of improvement. A precautionary approach that assumes a less productive stock and lower recruitment (i.e. red line in Fig. 3.10) should be used to estimate future TACs for the Patagonian grenadier fishery in the foreseeable future. A risk evaluation using management strategy evaluation (MSE; Smith et al. 1999) is the next step to assess and test the impact of including a recruitment shift, or not, on stock assessment outcomes (Chapter 4)

Having the best available information for the assessment is critical for the governance and management of this key fishery for Chile. Outputs from the stock assessment model (e.g. TAC recommendations) also have broader implications for industry sectors (catch and processing) and the community. Worldwide, it is estimated that marine fisheries supported 260 million full-time and part-time jobs either directly or indirectly (Teh and Sumaila 2013). Patagonian grenadier is an important ecosystem component and commercial resource that provides direct human labour (artisanal fishers, crews, processors, administrative staff, reparation of fishing gears, etc.) and indirect labour (Arancibia et al. 2015). A major challenge is to maintain a sustainable stock that delivers stable economic performance and livelihoods and does not jeopardize the ecosystem under a changing environmental future.

3.6 Acknowledgments

Funding for C.C-J. was provided by Becas Chile-scholarship (granted by CONICYT, Government of Chile) and CSIRO-UTAS QMS program. N. Klaer, A. Punt, J. Day (CSIRO) have provided comments on an early version of this study. I. Taylor and A. Whitten have provided support in SS and R4SS. Subsecretaria de Pesca (Chilean Government) has provided the data used in this study by the Citizenship Attention Integral System (SIAC).

Chapter 4

4 IMPLICATIONS OF A CLIMATE-INDUCED RECRUITMENT SHIFT IN THE STOCK ASSESSMENT OF PATAGONIAN GRENADIER (*Macruronus magellanicus*) IN CHILE.

4.1 Abstract

Patagonian grenadier (*Macruronus magellanicus*) is the most abundant demersal fisheries resource in Chilean Patagonia, and also is a key fisheries species in the south of Argentina and the Falkland Islands. Using the Stock Synthesis assessment platform, I show that the stock has declined in abundance off the Chilean coast. This has been attributed to a significant change in recruitment strength, and subsequent production, after 1999. To model a shift in the average level of recruitment, I include a year-specific environmental variable that adjusts the strength of recruitment resulting from the stock–recruitment relationship. Following establishment of a base-case assessment model for Patagonian grenadier (Chapter 3), a Management Strategy Evaluation (MSE) procedure was implemented to examine the consequences of incorporating a different model structure for recruitment values in the assessment which underpins the harvest strategy used to set the annual total allowable catch (TAC). A management strategy that does not consider a shift in recruitment resulted in average TAC values of approximately 125,000 tonnes, substantially above the sustainable yield of 45,000 tonnes when the recruitment shift was incorporated. A TAC based upon No Shift in recruitment would lead to unsustainable catches with significant impact on the ecosystem as well as the industry and coastal communities reliant on the industry if there was an actual shift in recruitment. Management of the

fishery since the recruitment shift occurred in 1999 has not incorporated a recruitment shift and total annual catch has been consistently below the estimated annual TACs. The current catch is around 40,000 tonnes, two thirds of the estimated TAC under a recruitment shift scenario. The history of the Patagonian grenadier fishery demonstrates the benefits of taking a precautionary approach that accounts for the change in fish productivity (whether climate-driven or otherwise). However, there can be considerable delays before a regime shift is observed in the recruitment data or an assessment model mis-specification is detected. The need for alternative approaches for providing more timely recruitment information is discussed.

4.2 Introduction

Climate change is recognised as a factor that can affect various processes in marine ecosystems, including abundance, biodiversity and phenological changes in marine populations (Doney et al. 2012; Todd et al. 2012; Visser & Both 2005). These changes can have significant implications for both the utilisation and conservation of natural resources. Climate change can directly and indirectly impact commercially important marine resources (Brander 2007). Climate driven changes in stock biomass can have consequences for recruitment and thus the future abundance of the species, their predators and their prey.

An important factor that can directly affect fisheries recruitment is ocean temperature, and major changes can potentially lead to regime shifts (Yasunaka and Hanawa 2005). Regime shifts are low-frequency, high-amplitude changes that can occur in oceanic conditions that may have especially pronounced effects on biological variables and propagate through several trophic levels (Collie et al. 2004). Such regime shifts have already been recorded in the early 1970s and mid 1980s in the Southeast Pacific, leading to changes in abundance of anchovy and sardine (Chavez et al. 2003; Alheit and Niquen 2004). Having a greater understanding of causes and consequences of regime shifts is important to allow managers the ability to appropriately adjust fishing effort to match shifts in productivity of the ocean environment (Rothschild and Shannon 2004).

Given that fish respond directly to climate variation, stock assessments should consider environmental variables as part of the traditional modelling and assessment frameworks (Maunder and Watters 2003; Methot 2011). Regime shifts and long-term changes in climate and/or the dynamics of climate variation may create changes in growth and mortality rates, the magnitude and frequency of high and low recruitment events, stock distributions, and abundance. Hollowed et al. (2008) show a framework for modelling fish responses including climate change variables. Adding environmental variables to assessment models has the potential to add realism to modelled scenarios and predictions and, in most cases this resulted in a greater level of precaution to account for the uncertainty of climate change impacts.

Recent studies have incorporated regime shifts in the stock assessment process for different species. A'mar et al. (2009) studied the impact of a regime shift in the North Pacific Ocean on management strategies for walleye pollock (*Gadus chalcogrammus*). They evaluated the current and four alternative management strategies with different definitions for the average recruitment for Walleye Pollock in the calculation of management reference points such as a 25-year sliding-window method and a dynamic initial biomass. They found that the sliding-window management strategy achieved the highest catches and the lowest interannual catch variation, but with a higher risk of overfishing. In Australia, a study of jackass morwong (*Nemadactylus macropterus*) (Wayte, 2013) used Management Strategy Evaluation (MSE) to assess the consequences of mis-specifying a regime shift that produced changes to the average level of recruitment. Wayte (2013) showed that the more precautionary scenario that meets the aims of the Australian Government's Harvest Strategy Policy is to assume that the recruitment shift has occurred. In this study, the MSE approach is used to analyse the consequences of including different recruitment scenarios for the Patagonian grenadier fishery in Chile.

Whether to include regime shifts into assessments can be a subjective decision, as evidentiary data and analysis may not be forthcoming. Klaer et al. (2015) proposed four criteria and a scoring guideline to establish whether a shift in stock productivity has occurred and should be included in stock assessments. Criterion 1 is observing changes in a productivity indicator. Patagonian grenadier has presented changes in productivity, showing 15 years of low spawning biomass and recruitments across multiple generations and different stock assessment outputs. Criterion 2 relates to an understanding of the assessment input data such as age/length at maturity and length-weight relationship. For Patagonian grenadier, there is some uncertainty in stock boundaries and catch levels due to unknown discard rates as well as uncertain growth parameters. Criterion 3 relates to the understanding of the assessment model structural assumptions. The assessment model shows annual recruitment residuals below average for the past 16 years, and the data fit is improved using a productivity shift that cannot be accounted for with a lower steepness. The last criterion (criterion 4) relates to biological explanatory hypotheses. Plausible mechanisms for a productivity shift in Patagonian grenadier have been suggested by Cubillos et al. (2014), and Castillo-Jordan et al. (2016) showing temperature effects on recruitment. In addition, Klaer et al. (2015) recommend that output from a biophysical or multispecies model should be consistent with observed patterns of change in productivity. However, no such model exists for Patagonian grenadier. Therefore, there are clear indicators that Patagonian grenadier may have undertaken a regime shift in recruitment, but further modeling and investigation should occur. This chapter explores how a regime shift in recruitment for this stock could influence and bias management decisions and the sustainability of the fishery.

Patagonian grenadier is the most abundant gadoid resource in Chilean Patagonia (41º40' to 52ºS) (Tascheri et al. 2010) and is also an important resource for Argentina (Ministerio de Agricultura, 2012) and the Falkland Islands (Falkland Islands Government, 2013). The species occurs in two geographical areas: the Southeast Pacific between Valparaíso (33º S) and Cape Horn (55º 58' S) in Chile (Arana, 1970 cited in Prenski et al. 2012), and in Argentina in the Southwest Atlantic between 33º S and 57º S (Wölhler and Giussi 2001 cited in Schuchert et al. 2010). Based on an assessment by Payá and Canales (2011), Patagonian grenadier has shown a decline in biomass, catch and catch rates in recent years. According to Payá and Canales (2011), the decline in biomass started in 2004, and was preceded by a considerable reduction in recruitment from 1999. This reduction was correlated with a shift to colder sea surface temperature in the main spawning/nursery areas of the species (Cubillos et al. 2014; Castillo-Jordan et al. 2016; Schneider et al. 2017).

In this chapter I aim to evaluate the management implications of ignoring or including a regime shift in the analysis of Patagonian grenadier fishery, using different scenarios of mis-specified recruitment shift in the assessment model and in the operating model.

4.3 Materials and methods

4.3.1 Stock assessment

A stock assessment for Patagonian grenadier was conducted using a statistical age- and length-structured model implemented in the software package Stock Synthesis (version 3.21d; Methot, 2011), and using data up to December 2013. The population dynamics model and the statistical approach used in fitting the model to the various types of data are specified in Chapter 3.

The assessment model is configured with an unexploited biomass and equilibrium age structure at the start of 1985 when the fishery commenced. It models the impact on the Patagonian grenadier population from four fishing fleets: two early fleets using different fishing methods, and two recent fleets corresponding to different fishing areas or fishing methods such as purse-seine and trawling (see Fig. 3.2, Chapter 3). Standardized catch rates are available for four of these fleets, and also for a period that overlaps two of the early fleets. Separate logistic functions are used for the length selectivity ogives for each fleet. The two parameters of the selectivity function for each fleet are estimated within the assessment. The rate of natural mortality, M, is set to 0.35 yr^{-1} and is configured to be age- and time-invariant (Chong et al. 2007). The parameters of the von Bertalanffy growth function are estimated within the model-fitting procedure from age-at-length data, with an assumption of no difference in growth by gender. A plus-group is modeled at age 15, and maturity is modeled as a logistic function with 50% maturity at 57 cm (Chong et al. 2007). The existing stock assessment model is configured with an equilibrium recruitment scenario with recruitment variability configured on hind cast estimates of recruitment since the beginning of the fishery (1985). In contrast, a Shift model is developed which uses the estimates from 1985 to 1998 for the period prior to 1999 and estimates from 1999 to 2012 for the period after 1998. The estimated parameters of the model are: average recruitment at unfished equilibrium spawning biomass *SB*, recruitment deviations from 1985 to 2012, and fishing gear selectivity parameters.

The data used in the assessment comprise: landed catches from 1985 to 2014, standardized catch per unit effort by fleet (cpue), age-at-length data, independent surveys and an aging error matrix. Each data source (except for catch) is available for only some fleets and years (Table 3.1, Chapter 3, data available in appendix).

I model a climate-induced shift in the stock assessment by estimating two initial recruitment values ($R_{o\ in\ 1985}$ and $R_{o\ in\ 1998}$). Two scenarios have been analysed in the stock assessment model by using the parameter for considering environmental variables (ρ_{env}) in the Stock Synthesis platform. This parameter has an influence on the total recruitment variability that will be explained by the environmental effect. The environmental effect is lognormal, and when it is included in the model, the arithmetic mean recruitment level will increase above the level predicted by the spawning biomass (Methot, 2011). The initial ρ_{env} value for the different scenarios, will depend on the initial recruitment values $R_{o\ in\ 1985}$ or $R_{o\ in\ 1998}$. If the scenario does not account for a recruitment shift, the ρ_{env} value will be near to zero. In contrast, if the scenario includes a recruitment shift, the expected ρ_{env} value should remain at the initial point (ρ_{env} = 1.186).

4.3.2 Recruitment modeling

The stock recruitment relationship includes a period without a recruitment shift, and another including a recruitment shift. The estimated annual recruitments follow a log-normal distribution about an underlying Beverton-Holt stock-recruitment relationship (SRR), parameterized by the average recruitment at unfished equilibrium spawning biomass (*SB*), initial recruitment (R_o), and the steepness parameter (*h*)

$$R_t = \frac{4hR_0 SB_t}{SB_0 (1-h) + SB_t (5h-1)} e^{\varepsilon_t - 0.5\sigma_R^2}$$

where SB_t is the *SB* at the beginning of the year *t*, *Bo* is the unfished equilibrium *SB* corresponding to R_o, ε_t is the recruitment deviation in year *t*, and σ_R^2 is the variance of the recruitment in log-space. Recruitment deviations are estimated for 1985 to 2012.

4.3.3 Management strategy evaluation

Management strategy evaluation (MSE, Fig. 4.1) is used to evaluate alternative options for management in the fields of natural resource decision analysis (Butterworth et al. 2010; Punt et al. 2014). In this case, we use MSE to assess the effect of a recruitment shift in the stock assessment model against a model that does not consider the shift for the Chilean Patagonian grenadier fishery. We define a management strategy as composing (i) the data collection process, (ii) an assessment of stock status and (iii) a decision rule that translates stock status into a management action (e.g setting the TAC). The operating model, which describes the 'true' system dynamics (e.g. Smith et al. 1999; Punt et al. 2001a; Wayte and Klaer 2010; Wayte 2013) is a mathematical model of the population dynamics of the fish, and behavior of the fishery, including any known and/or hypothesized environment influences. The operating model is first projected over a historical catch period for Patagonian grenadier, and age–composition data are generated using the known 'true' population dynamics represented by the operating model. Fay et al. (2011) described in detail the operating model that represents the 'true' fish dynamics and multi-fleet dynamics model.

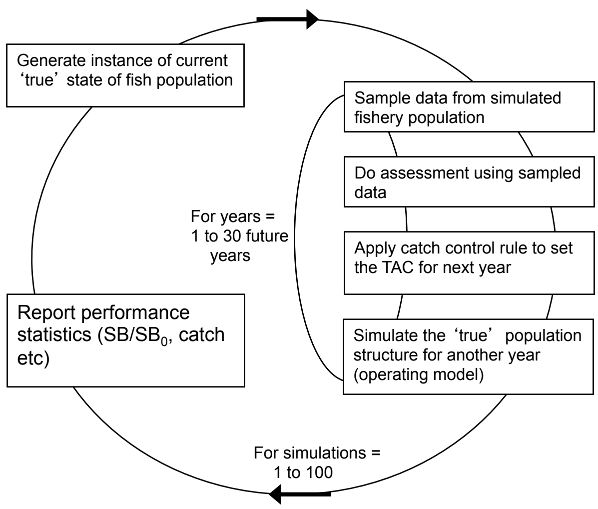


Fig. 4.1. Schematic diagram for Management Strategy Evaluation (MSE) (adapted from Sainsbury et al. 2000).

The MSE is run for four scenarios (Table 4.1), with all of the combinations of the operating 'true' model and the assessment model with and without a recruitment shift. In particular, this allows an examination of the influence of getting the assessment wrong, namely, a mis-specification in the assessment model structure in comparison to reality (i.e. Table 4.1, scenarios b and d). The simulations include 30 years of the fishery population model projected into the future, and each scenario includes 100 simulations. The simulations show differences with observation error in the generated data and process error in the operating model population dynamics (future recruitment deviations).

Table 4.1. MSE scenario description for Patagonian grenadier.

Scenario	Operating model	Assessment model
a	No-Shift	No-Shift
b	No-Shift	Recruitment shift
c	Recruitment shift	Recruitment shift
d	Recruitment shift	No-Shift

4.3.4 Risk criteria

To determine the sustainability of the fishery and to provide TAC levels for projected years, I use a harvest strategy framework (HSF) based on Australia fisheries (Smith et al. 2008). The HSF is used to provide TAC levels based on harvest control rules (HCR) that establish a recommended biological catch (RBC). A successful HCR will provide an appropriate response to deviations from management targets, be robust to key uncertainties, and emphasize precautionary action given uncertainty (Fay et al 2011). Since Chile does not include a formal HCR for the Patagonian grenadier fishery, I used Tier 1 HCRs based on the Southern and Eastern Scalefish and Shark Fishery, which includes the Australian blue grenadier fishery. This rule includes a 20: 35: 48 strategy (B_{lim}: B_{msy}: B_{targ}) (Tuck et al. 2013). B_{lim} is the limit biomass reference point below which the spawning biomass is considered overfished; it is 20% of the unfished spawning biomass. B_{msy} represents the spawning biomass reference point at which maximum sustainable yield (MSY) can be achieved. B_{targ} is the spawning biomass level which is equal to the biomass at the maximum economic yield (MEY). The default proxy used for MEY is 1.2 * B_{msy} or $B_{48\%}$ of the unfished spawning biomass (Punt et al. 2016).

4.4 Results

4.4.1 Recruitment variability

The No-Shift scenario (Fig. 4.2a-c), which includes recruitment values from 1985 to 2014, shows a gradual decline in relative biomass (*By/Bo,* where *By* is the biomass in a particular year and *Bo* is the initial biomass) from 1985 until 1999, after which it declines more steeply falling below B_{targ} in 2002 and B_{lim} in 2006 (Fig. 4.2a). The residuals for this model show a pattern of above average recruitment until 1999 and below average recruitment until 2013 (Fig. 4.2b) and the variability in recruits (Fig. 4.2c) show a limited relationship to spawning stock size for the higher recruitment period prior to 1999. In contrast, the stock assessment that includes the recruitment shift (Fig. 4.2d-e) shows a biomass depletion above the limit reference point (B_{lim}) for the last four years, since biomass is compared with a lower initial reference biomass in 1998 (Fig. 4.2d). In addition, the recruitment deviations in the recruitment shift assessment provide a better fit to the data (Fig. 4.2e) as the new model has two stock recruitment relationships for the high and low productivity periods (Fig. 4.2f).

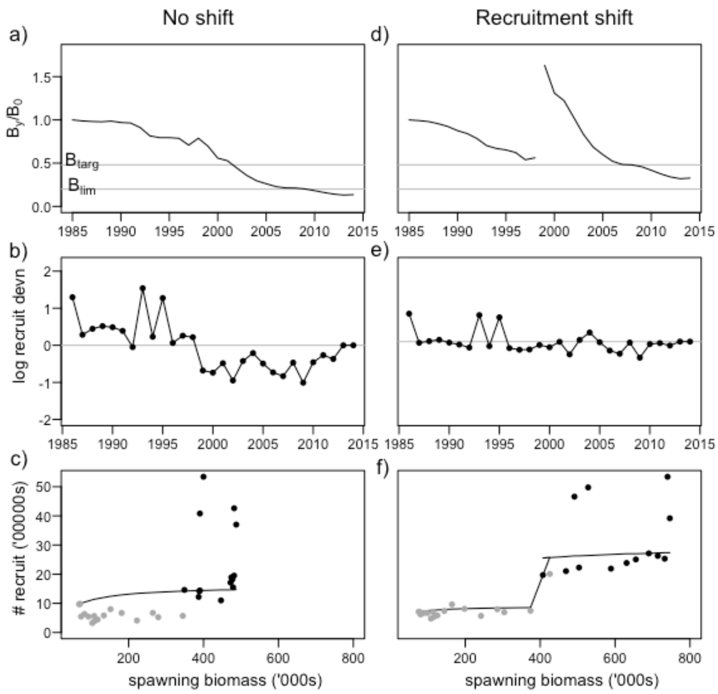


Fig. 4.2. Results of the stock assessments using the 'No-shift' and 'Recruitment Shift' assumptions. a&d) Stock status over time (The horizontal grey lines show B_{lim} and B_{targ}). b&e) the recruitment deviations estimated for both models. c&f) stock-recruitment relationship (black line), and estimated annual recruitments for the Patagonian grenadier fishery (grey points shows period from 1985 to 1998 and black points from 1999 - 2014).

4.4.2 Management strategy evaluation (MSE)

The projected relative biomass and TAC from the MSE are summarized for the four scenarios in Figure 4.3. If the operating model (the 'truth') had 'No-Shift' in the stock productivity then the unfished equilibrium spawning biomass is based on that in 1984 (SB_{1984}). Alternatively, if the operating model includes a 'Shift', then a new stock recruitment curve (Fig. 4.2f) is estimated and applied for years after 1998 and the equilibrium spawning biomass is based on that in 1998 (SB_{1998}). Stock assessments are undertaken for each of these operating models which accept the true situation as well as scenarios where the assessment model is mis-specified (i.e. a 'Shift' operating model with a 'No-Shift' assessment model).

For the operating model with 'No-Shift' (True: No-Shift), the relative biomass and TACs (Fig. 4.3 a and b) show minimal difference whether a regime shift is included or not included in the stock assessment. Although the target biomass is achieved after seven years, there is very high uncertainty in the estimated biomass ratio. Irrespective of whether the assessment model is mis-specified, the TAC rebuilds to around 125,000 tonnes after approximately 10 years. In contrast, mis-specification of the operating model with a Shift (True: Shift) results in the biomass ratio never reaching the target biomass during all of the forecast years (Fig. 4.3c and d). The TAC is similar whether the assessment model is mis-specified or not although, for the mis-specified assessment model, the TAC shows considerable variation for the first 10 years, before recovering to a similar value to the scenario where a shift is configured in the assessment model (Fig. 4.3c and d). The long-term sustainable TAC is predicted to be approximately 45,000 tonnes if a recruitment shift has occurred.

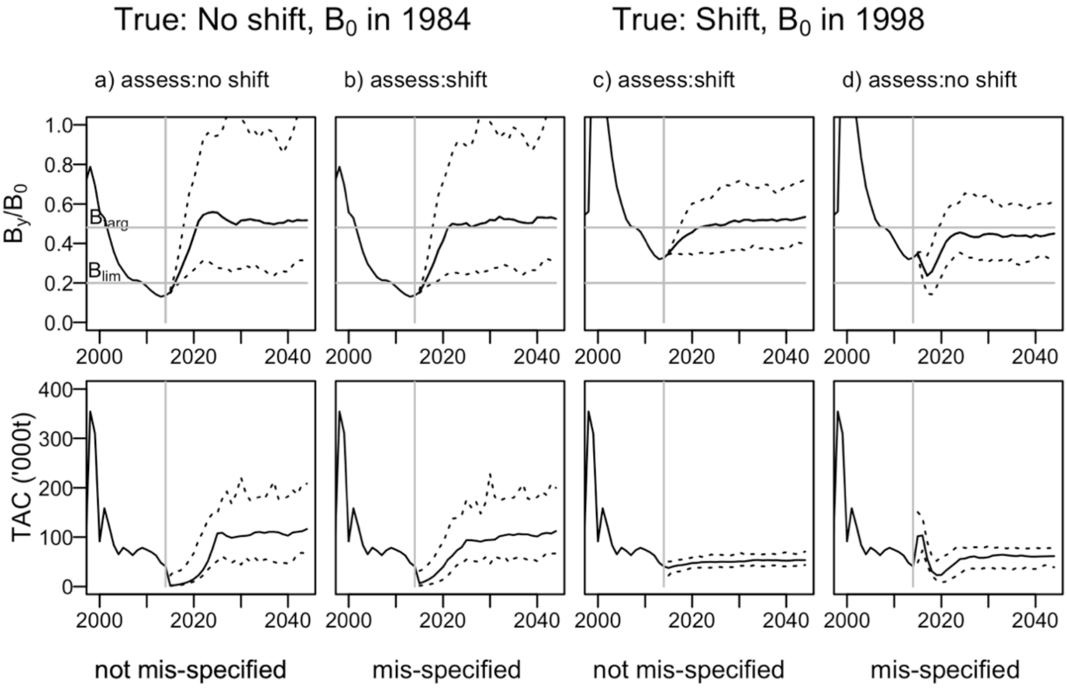


Fig. 4.3. Time-trajectories (median, and 2.5 and 97.5 percentiles (dash lines) over 100 simulations) of 'true' stock status (B_y/B_o) and TAC (thousands tonnes) for the MSE scenarios (Table 4.1, when the true model is the operating model and the assess is the assessment model). The vertical grey line shows the starting point for the projection period. The horizontal grey lines show B_{targ} and B_{lim}. Models are not mis-specified when the true model and assessment model are the same, and models are mis-specified when the assessment model and true model differ (i.e. true model includes a shift when a shift assessment is included in the assessment model).

Given that mis-matches between the assumptions underpinning fish stock assessments and actual fish and fishery dynamics are a reality of stock assessments, an important management question to consider will be how many years it takes for a mis-match between the stock assessment (that is configured a shift in recruitment) and the operating model's reality (where there is no shift) to be recognized through the assessment model's estimation process. While recent recruitment's may be lower than expected (since 1999 for example), in reality there may actually not have been a long-term shift to lower recruitment. However, not unexpectedly, assessment scientists and managers may unwittingly assume a shift has occurred. Given there is no shift, the data on recruitment provided to the assessment model from the operating model should, over time, provide an indication that recruitment has recovered from the brief lower period and is now "average". As the assessment model has an estimated environmental parameter, ρ_{env}, the value of this parameter should decline over time to the "no shift value" of zero as the data informing the assessment model show stronger indications of good recruitment. This can be observed by plotting the trajectories of ρ_{env} over time (Fig. 4.4a). The estimated environmental parameter (Table 4.1, scenario b) shows a consistent decreasing trend across time (Fig. 4.4a), with the median initial estimated value across all simulations being 0.64, reducing to 0.27 at the end of the projection period (Fig. 4.4 dash line). This result is consistent with the TAC projections (Fig. 4.3b) that shows similarities between scenario a and b (Table 4.1 and Fig. 4.3). Because the assessment model that is configured with a shift is structurally trending toward an assessment model with no shift (as ρ_{env} tends to zero) it is not surprising that Figures 4.3a and 4.3b appear similar.

If there is no mis-match, and the assessment model correctly is configured with assumptions a Shift in a Shift 'true' scenario, the estimated environmental parameter should be closer to the initial 'true' value of ρ_{env} assigned by the conditioning of the operating model, in this case ρ_{env} = 1.186. Figure 4.4b shows this is the case, with the estimated environmental parameter generally near the actual value of 1.186. The estimated values of ρ_{env} are higher than the actual value because the MSE scenario does not include the bias ramp method that can affect the recruitment variability that is connected to ρ_{env} (Methot and Taylor 2011). Note that the initial median values of the ρ_{env} are different in Figures 4.4a and 4.4b. This is because the No-Shift 'true' operating model has a higher *Ro* and *Bo* than the Shift 'true' operating model.

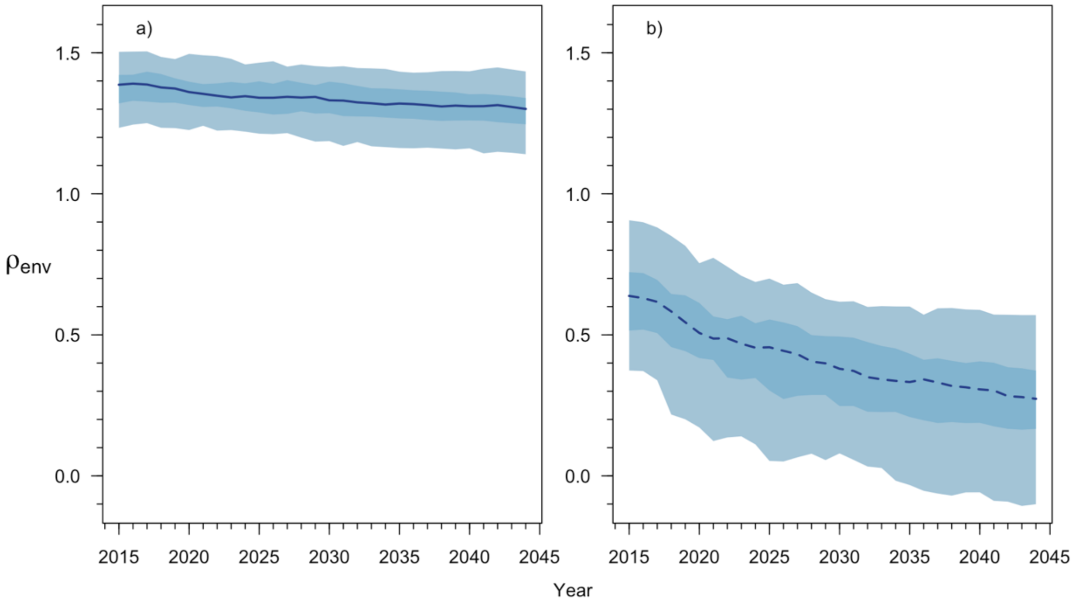


Fig. 4.4. For an assessment model that is configured with assumptions a shift in recruitment, shown are the median, 50% and 95% confidence intervals of the estimated environmental parameter $\boldsymbol{\rho_{env}}$ if the operating model (a) has a shift in recruitment and (b) if the operating model has no shift in recruitment.

The no regime shift scenarios for the operating model (Fig. 4.5, scenarios a and b) show substantial differences between the average TAC for the final 10 years of projections compared to the Shift models (Fig 4.5, scenarios c and d), with 150,000 tonnes for the No-Shift and 60,000 tonnes for the shift scenarios (Fig. 4.5i). The incorporation of a false scenario into the true situation (e.g. Shift model when no shift occurs or No-shift model when shift occurs) has very little impact on the final TAC but does reduce the stock status below the B_{targ} reference point when a shift does occur and is mis-specified as no-shift in the assessment model (Fig. 4.5ii, scenario d).

The minimum final stock status does not show a big difference in No-Shift models, but with the a and b scenario (Table 4.1) the lower 95% confidence interval value is just below the limit reference point irrespective of whether the assessment model is mis-specified or not (Fig. 4.5iii). All the scenarios demonstrate that there is 100% probability of a value of the median minimum 'true' stock status in the final 10 years being above the 20% biomass limit (Fig. 4.5iv).

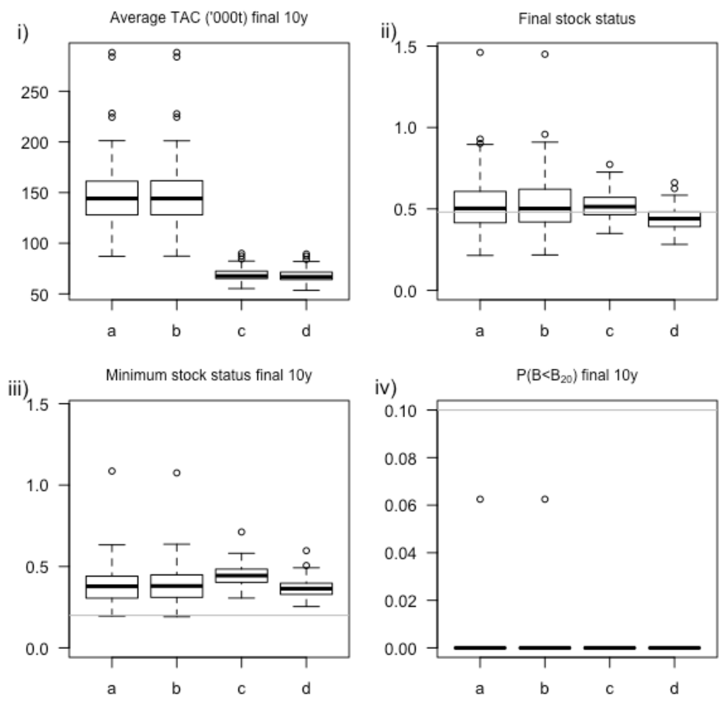


Fig. 4.5. Box plots of performance statistics for the four MSE scenarios described in Table 4.1. (i) shows the average TAC in the last 10 years for the projection period, (ii) shows the 'true' final stock status for the final year's projection (gray line shows the target stock status), (iii) shows the 'true' minimum stock status for the last 10 years (gray line shows the limit stock status) and (iv) shows the average of the final 10

years of stock status and the median probability of the SB falling below the reference point limit.

4.4.3 Implications of mis-specification of a regime shift.

The Patagonian grenadier fishery demonstrates the impacts of mis-specifying a regime shift. Despite a recruitment regime shift potentially having occurred in 1999 the fishery continued operating under a No-Shift scenario similar to Table 4.1 scenario d. The TAC projections from the annual assessments by the Chilean government (Fig. 4.6) had been over-estimated with annual realized catches being substantially lower than the estimated TAC from 2000 to 2012. The six years from 2005 to 2010 had approximated the same values as the No-Shift model predictions from the No-Shift assessment in this chapter. Since 2010, the fishery has seen catches decline to around 40,000 tonnes. Although catches from 2004 to 2011 were above the estimated sustainable catch of 60,000 tonnes from the "Shift" model, these catches do not appear to be sustainable and overfishing of the stock has led to total annual catches which are now two-thirds of the long-term sustainable catch estimated from the "Shift" model. Thus if a "Shift" model had been implemented in 2004, when the impact of the recruitment shift was entering the fishery, a 60,000 tonnes TAC would have seen a small loss of catch initially prior to a higher sustainable catch in later years.

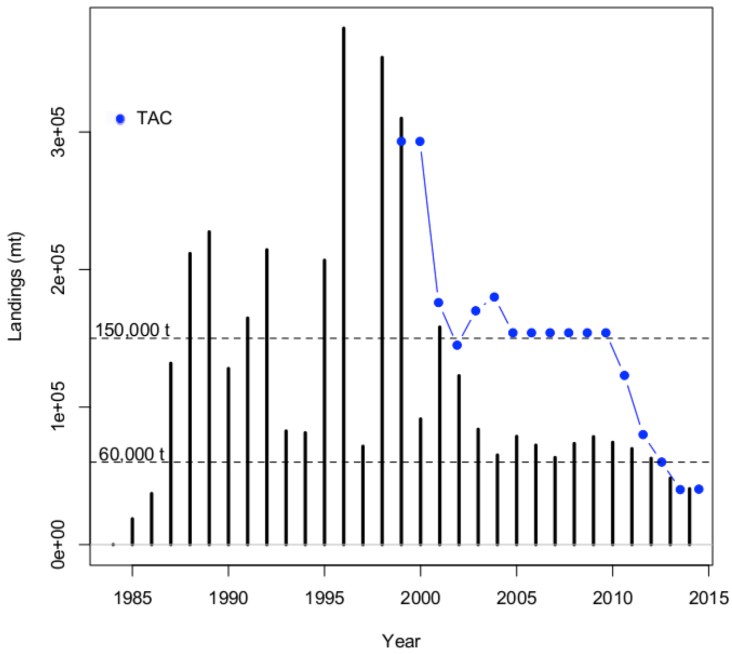


Fig. 4.6. Total landed catch by fleet of Patagonian grenadier from 1985 to 2014 and the actual TAC for the Chilean Patagonian grenadier fishery. The TAC estimates from the "No-Shift – 150,000 t" and "Shift – 60,000 t" models from assessment model developed in this thesis are shown as dotted lines.

4.5 Discussion

A regime shift in the recruitment of Patagonian grenadier has been identified along the coast off Chile, correlated with the changes in water temperature adjacent to the coast of southern Chile (Cubillos et al. 2014; Castillo-Jordan et al. 2016). Cubillos et al. (2014) presented evidence that changes in recruitment in 2000 do not match any observed shift in spawning biomass. However, Patagonian grenadier spawning biomass has shown a progressive decline between 1996 and 2002 (Payá 2014 and Chapter 3). In addition, the Patagonian grenadier catch has also reduced from historic levels in the 1990s with catches over 300,000 tonnes decreasing to approximately 40,000 tonnes in recent years. This study tested the consequences of ignoring or including a recruitment regime shift in the stock assessment model. The No-Shift model predicts an initial continued decline in TAC to approximately 5 tonnes before gradual rebuilding over the next decade to a long-term average TAC of 125,000 tonnes. However there is large uncertainty around the TAC estimate reflecting the large variability in recruitment estimates prior to the regime shift in 1999. In contrast, the Shift model estimates a substantially lower TAC of 45,000 tonnes based on the lower recruitment estimates since 1999 with rebuilding from the current 40,000 tonnes commencing immediately. Since 1999 estimated recruitment has also been less variable (Fig. 4.3 a and b). The MSE results show that if a recruitment phase shift has occurred and it is not accounted for in the stock assessment model the biomass would decline to levels below the target level (Fig. 4.3d). This is the current status of the Patagonian grenadier fishery whose landings in 2014 were two thirds of the estimated TAC for the true shift model and declining.

Given the focus on precautionary approaches to fishing (FAO 1995), assuming a regime shift in recruitment when estimated recruitments are consistently low should provide a precautionary approach. Considering lessons from other fisheries, such as northern cod off Newfoundland, Walters and Maguire (1996) suggested that errors in a stock assessment that provide optimistic forecasts can contribute to overfishing, which has implications in the build-up of overcapacity from unrealistically higher TACs. In addition, overfishing for recruits can lead to fisheries collapse, implying that harvest rate targets should be lower than currently is configured, especially when uncertainty is significant (Walters and Maguire, 1996).

Changes in recruitment levels are being observed in several fisheries, especially those with longer larval life cycles (*Jasus edwardsii* (Linnane et al. 2010), *Panulirus cygnus* (Caputi et al. 2013), *Latris lineata* (Tracey, pers.comm.), *Nemadactylus macropterus* (Wayte 2013)). With global warming predicted to more than double the current temperature estimates by the end of the century (IPCC 2014), changes in recruitment patterns are likely to become more common. However, obtaining estimates of recruitment is difficult, with most commercial fish species relying on back calculation of otoliths obtained from the commercial catch to determine recruitment strength. Patagonian grenadier enter the fishery at ages 4-5 years. A minimum of at least 3 years would probably be required before a change in recruitment could be considered more than a random fluctuation. Thus the fishery would have been fishing at a much higher level than sustainable for at least 3 years.

Ways to overcome this hiatus would be to measure larval recruitment more directly (e.g. lobster fisheries that measure larval settlement on artificial substrates (Gardner et al. 2001)), develop a relationship between spawning stock and recruitment, or linking recruitment to factors that effect larval survival and/or recruitment to the fishery and therefore provide 'defacto' measures of recruitment. Patagonian grenadier's larval recruitment regions are poorly understood and direct measurements of larval recruitment are not possible. As the larval period prior to recruitment to the demersal life-history phase is around 60 days of age (Horn and Sullivan 1996; Balbontin et al. 2004; Krusic-Golub et al. 2007) there is likely to be environmental influences that may dampen any signals from a stock-recruitment relationship. In species where a stock recruitment relationship is unable to predict changes in recruitment, 'defacto' indices may provide improved resolution of recruitment. Such indices may include environmental parameters that enable larvae to find suitable habitat (e.g. wind and ocean currents facilitating dispersal) or sufficient food (e.g. chlorophyll counts or position of upwellings or oceanic fronts) or avoiding predators. With increased ocean warming predicted, there is expected to be impacts on fish stocks. Improving our understanding of the linkages between increased warming of the oceans and recruitment in fish stocks will be necessary to ensure that changes in fisheries productivity are recognised as early as possible and managed appropriately. Early warning will also provide greater lead in time for fishing industries to adjust.

The stock assessment model developed in this thesis uses the Stock Synthesis platform which allows incorporation of environmental data through the link parameter. This enables increased predictive power of the models and to better reflect variability in key stock assessment parameters such as recruitment. The environmental time series drives the expected recruitment deviation through the estimated link parameter. The inclusion of environmental parameter effects (e.g. regime shift) on biological factors (e.g. stock recruitment curve) in the model helped to explain and provide a better predictive power of recruitment variation and its influence on the TAC projections. The environmental link parameter showed a low deviation value for the Shift 'true' operating model, being relatively consistent with the value that estimated the shift. The environmental parameter for the No-Shift model demonstrated a shift to the true model (moving towards zero) indicating that the main impact of mis-specification of a recruitment shift when it is not occurring is short-term underestimates of TAC over 30 years projections. In contrast, mis-specification of the recruitment shift when it is occurring resulted in the target stock reference limit for the fishery never being achieved. Thus from a precautionary perspective, mis-specification is primarily an issue when change does occurs and is not accounted for in the model

Stock recruitment forecasts in conditions of constant change for species and habitat will be a crucial part of fisheries science in the future and necessary if we are to use our marine resources optimally for both social and economic benefits. In the case of the Patagonian grenadier fishery, a period with high recruitment has occurred before 1999, followed by a low recruitment period. Fisheries models need to be updated to actual conditions, and be considered in harvest control rules, policy and management decisions. Subbey et al. (2014) remarks that models forecasting recruitment need to be more precise even when environmental covariates are included as explanatory variables. Establishment of new environmental data sets that help to explain recruitment variability, such as those suggested in Chapter 2, and updates checking for change in the stock recruitment curve could be developed in a next step to determine the influence of environmental variables or climate indices in the recruitment of Patagonian grenadier.

This is the first MSE approach for Patagonian grenadier in Chile, showing that this methodology can be a strong tool for managers to test different scenarios of interest. Our results conclude that Patagonian grenadier does not show considerable differences in depletion when the regime shift is included in the assessment model in a No-Shift 'true' scenario. As this analysis replicated the Chilean analysis for Patagonian grenadier stock assessment, the MSE true model (No-Shift and Shift) only represents the parameter uncertainty from the stock assessment developed. Future MSE analysis should include additional uncertainty in parameters that are fixed in the assessment model, such as natural mortality, steepness, and the environmental link. The environmental link parameter needs to be least biased and match the operating model in the same way as the stock assessment.

With increased temperature in the climate change projections for the next century, it is predicted that global oceans will warm and this will have consequences for winds and ocean currents. Already we are seeing changes in the distribution, abundance and phenology of marine species. While many of these changes have been associated with species moving to preferred habitats (regime shifts), a major impact on abundance can be associated with recruitment where species are dependent on currents to distribute larvae to appropriate juvenile habitats, to carry larvae to regions of sufficient food or regions to minimise predation. This study adds to the growing list of species where recruitment has shown unexpected changes resulting in substantial changes in stock productivity. As a precautionary approach, declines in recruitment that are sustained for 3 years should initiate decision makers to consider implementing recruitment shift models in their assessments for setting TAC.

4.6 Acknowledgments

Funding for C.C-J. was provided by Becas Chile-scholarship (granted by CONICYT, Government of Chile) and CSIRO-UTAS QMS program. S. Wright and T. Raymond (AAD), N. Klaer (CSIRO) have helped to improve the manuscript.

Chapter 5

5 GENERAL CONCLUSIONS

Fish are an important source of food for people worldwide. According to the Food and Agriculture Organization of the United Nations (FAO 2016), annual world per capita fish supply reached 20 kg in 2014. In addition, fishes are one of the most-traded commodities around the world; with the major export contribution coming from developing countries (FAO 2016). With fish being such a valuable resource for nutrition, export and livelihoods it is important that these marine resources are managed optimally. Having the correct information to determine catch targets and limits beyond which resources are unsustainable is essential for good management of marine resources for future generations. Fisheries management requires good scientific understanding of the biology, ecology and behaviour of the exploited stock to establish target reference points that ensure that stocks are at sustainable production and at a low risk of overfishing (Beddington et al. 2007).

A classical target reference point commonly used in fisheries management is the estimated biomass level necessary to produce the maximum sustainable yield (MSY). In fisheries, MSY is defined as the maximum catch (in numbers or mass) that can be removed from a population over an indefinite period (Maunder 2008). Models that determine MSY have been interpreted as static invariant parameter models, using fixed catches per year. Such models are increasingly being seen as inappropriate since they ignore the natural variability in abundance that is inherent in fish populations. Assumptions of a constant catch that do not account for the dynamics in fish stocks can lead to stock depletion and overfishing (Mace 2001).

Fisheries have mostly been managed with limited regard to the environmental impacts on the dynamics of the stock, often by assuming equilibrium or deterministic dynamics around key processes (e.g. recruitment variation). However, with the increased recognition of the impact of non-stationary environmental variables and the potential for permanent changes (e.g. regime shifts), there is a greater need to incorporate environmental variables into fisheries modelling and assessment frameworks. Using a more flexible framework that can provide multiple options for testing sensitivities, such as the ability to include new data sets, estimation of new parameters or the inclusion of environmental variables to the stock assessment model is becoming acceptable as researchers and managers attempt to refine stock predictions (Haltuch and Punt 2011; Ianelli et al. 2016).

Climate change is recognized as a factor that can affect a number of processes in marine ecosystems but understanding the impacts is one of the challenges for the optimal use and management of marine resources into the future. To appreciate the full impact of climate change on the marine system it is necessary to understand the impact of climate change on the abundance and distribution of a given resource. A key process that affects the productivity of marine resources is their on-going recruitment. Fished species often have planktonic larval stages that are considered sensitive to changes in currents (distribution) and productivity (predator-prey relationships). Recruitment variability can be an essential influence on living marine resource dynamics since a successful survival rate in the first stage of life can lead to a healthy biomass in the future. This first stage of life can be affected by a range of biotic or abiotic effects. Given that the world is changing, it is important for stakeholders to consider how these changes affect marine fisheries. In addition, fisheries have been exposed to overfishing, pollution and other anthropogenic causes that already place stress on the world's fish populations (Pauly et al. 2002; Worm et al. 2006; Sumaila et al. 2011).

In this thesis, I have focused my research on fish recruitment to explore the impacts of a uni-directional change on fisheries assessment. Recruitment is highly sensitive to changing climate impacts and I used this key stock assessment parameter to demonstrate how variation in this parameter can impact population size, exploitable biomass, and future catch. Chapter 2 takes a global outlook by considering commonality in recruitment variability across commercial Southern Hemisphere fish stocks and also linking their recruitment patterns with global climate indices. Global climate indices such as IPO, SAM and SOI are basin scale indices that are considered to be an ENSO indicator and drivers of winds, ocean currents and temperature distribution that can affect the ecosystem. Although affecting large geographic regions, the impacts of change in these indices can impact regional and finer scale changes in local winds and temperature across these regions. As such, these indices may help explain variation in recruitment to fish stocks. My results suggest that there are similarities in recruitment patterns at ocean basin scales (e.g. for hakes and lings) and at regional scales (e.g. jackass morwong, blue grenadier and Patagonian grenadier). It is the first study to analyse different species across the Southern Hemisphere, and by identifying the importance of climate indices that help explain the estimated variability in recruitment, these indices show promise for monitoring and predicting future catches. Three common recruitment patterns explained recruitment variability for most fishes in the Southern Hemisphere. However, some species did not show a clear grouping within these patterns (e.g. toothfish and silver warehou) suggesting that in some cases different drivers are affecting the life stages of these species.

Patagonian grenadier, one of the Southern hemisphere species analysed, is the main demersal fishery in Patagonia. This species is economically important in Argentina, Chile and the Falkland Islands. The Chilean Patagonian grenadier fishery has seen substantial change over the last 25 years, resulting in changes in targeting, fishing methods and fleet distribution. Thus there is a recent history of increases and decreases of biomass in the fishery. Catches of Patagonian grenadier initially increased to a peak of over 300,000 tons in the 1990s before declining to current levels of 40,000 tonnes in 2013 and 2014. The decline in landings for the Chilean stock of Patagonian grenadier has been related to a concurrent recruitment decline, which has a match with sea temperature changes described by Cubillos et al. (2014) and Schneider et al. (2017). The poleward displacement of the South Pacific High has resulted in water-column cooling and sea surface salinity increases in the upwelling region off central-south Chile where the Patagonian grenadier fishery operates (Schneider et al. 2017).

To undertake an assessment that allows for variability in environmental inputs I developed an age-structured model using the Stock Synthesis platform (Chapter 3). An advantage of Stock Synthesis is that the environmental link parameter can be turned on and off so that the effect of the parameter on the model can be compared for the current status and for future projections. In this thesis, I used the environmental link parameter to determine the impact of a recruitment shift on the fishery as well as the outcomes if the recruitment shift was mis-specified. Another advantage in using the Stock Synthesis platform has a growing user base (Methot and Wetzel 2013; Punt and Maunder 2013; Wayte 2013). Thus models and new developments (e.g. using the environmental link parameter) can be internationally peer reviewed and issues (e.g. bugs) identified and supported by others. A disadvantage of this integrated modelling platform can be the complexity of the equations and thus model development often requires greater upfront investment in time. This complexity can also carry forward as an increased difficulty in explaining model outputs and how they were derived to stakeholders, especially in periods when harvests are being reduced and stakeholders are increasingly nervous about their future.

Based on the outcomes of the stock assessment model I evaluated the management implications of ignoring or including a regime shift in the analysis, using different scenarios of mis-specified recruitment shift in the assessment model and in the operating model. By evaluating the impacts of the different management scenarios, it is possible to determine the consequences of using a wrong model in an assessment structure and its subsequent effect on the biological and human systems. In the Patagonian grenadier fishery, ignoring a recruitment shift when it has occurred provided over-optimistic catch projections of 150,000 tonnes when sustainable catch projections that accounted for the recruitment shift were only 60,000 tonnes. Not only is the catch unsustainable biologically, the reduction in the catch of this magnitude will have substantial impacts on fishers and others that rely directly or indirectly on the industry.

An issue with incorporating recruitment shifts into assessment models is the time lag in identifying a recruitment shift. For species such as Patagonian grenadier where recruitment indices are determined from hind casting of catches (length-age models) or back-calculation from otolith readings from fish sourced from the commercial catch, the change in recruitment may only be seen 4-5 years after the fish have recruited. As many of these stocks have relatively high variability in recruitment, it can be many years before a trend is determined. By not incorporating a recruitment change when it has occurred (i.e. mis-specification) there can be considerable initial variability in catches followed by the long-term catches that never reach the target reference point for the fishery. Although the end result is a substantially lower TAC, predicting this decline does provide industry with time to readjust rather than, as happened in the Patagonian grenadier fishery, fishers and managers constantly believing, and making investments on over optimistic TACs. To prevent these unfavourable events, it is necessary to take into consideration or follow the components of the precautionary principle. The precautionary principle, is a guideline that has four central components: taking preventive action in the face of uncertainty; shifting the burden of proof to the proponents of an activity; exploring a wide range of alternatives to possibly harmful actions; and increasing public participation in decision making (Kriebel et al. 2001). Following this approach, I suggest that more attention should be directed towards increasing our understanding of recruitment and encouraging managers to adopt preventative actions earlier by exploring potential recruitment changes. My results show that mis-specifying a recruitment shift when it does not occur has little impact on overall TAC and this was also found by Wayte (2013). Thus it would be more prudent to model a recruitment shift with only limited data than wait for trends to occur and the fishery to be overestimating catch and overharvesting the resource. By using additional information such as linkages with global climate indices, modellers can start to build increased confidence in the potential recruitment shift situation. For instance, if a marine resource has one or two years of low recruitment and, in addition, climate indices are suggesting low recruitment, there should be enough evidence to implement a precautionary approach and incorporate a recruitment decline. Such early warning should also enable stakeholders to consider the probability of lower TACs.

In this thesis I have demonstrated that the global climate is an important explanatory variable that can help understand recruitment variability in southern hemisphere fish stocks. With future climate change scenarios for global warming at the end of the century predicted to reaching over 2°C, a more than doubling of the previous warming, climate would be expected to be one of the most importance drivers for changes in the abundance and distribution of fish stocks. At the local level of the individual fish stock it will become increasingly important to monitor fish recruitment for longer-term change to ensure that the world's marine resources are sustainably managed and provide optimal ecosystem goods and services. In 2016, FAO estimated that 56.6 million people work in activities associated with fisheries and aquaculture with 36% working full time, 23% part time and the rest working sporadically. Ensuring sustainable harvests from marine resources needs to ensure that fishing industries and communities can be prepared for changes in fish abundance, especially when it is a decline. Applying recruitment shifts into assessment models, even when data is limited (e.g. 2 years of decline) should be used both as a precautionary measure as well as providing industry with potential insights into the changing future. Even a one year drop to a level substantially lower than the average recruitment should stimulate a greater focus on the collection of recruitment data for that resource. Given the magnitude of declines already observed in several fisheries, an increased focus on understanding and determining recruitment variability and the role of environmental factors will be necessary for the management of global fish stocks and their associated industries. Research needs to focus on both basin and regional scale trends as well as species-specific responses. Species that are more susceptible to climate change due to life history features, such as long larval periods, are most likely to require extra attention.

6 REFERENCES

A'mar, Z. T., Punt, A. E. & Dorn, M. W. 2009. The impact of regime shifts on the performance of management strategies for the Gulf of Alaska walleye pollock (*Theragra chalcogramma*) fishery. Can. J. Fish. Aquat. Sci, 66, 2222-2242.

Alheit, J. & Niquen, M. 2004. Regime shifts in the Humboldt Current ecosystem. Progress in Oceanography, 60, 201-222.

Alheit, J., and Bakun, A. 2010. Population synchronies within and between ocean basins: Apparent teleconnections and implications as to physical-biological linkage mechanisms. J. Marine Syst. 79: 267-285.

Anderson, C. N. K., Hsieh, C. H., Sandin, S. A., Hewitt, R., Hollowed, A., Beddington, J., May, R. M., Sugihara, G. 2008. Why fishing magnifies fluctuations in fish abundance. Nature. 452: 835–839.

Arancibia, H., T. Pitcher and M. Livingston. 2015. An overview of hake and hoki fisheries: analysis of biological, fishery and economic indicators. Hakes: Biology and Exploitation. Arancibia ed. 324–340.

Bakun, A. 1996. Patterns in the Ocean: Ocean Processes and Marine Population Dynamics. University of California Sea Grant, San Diego, California, USA, in cooperation with Centro de Investigaciones Biologicas de Noroeste, La Paz, Baja California Sur, Mexico. 323 pp.

Balbontin, F., Uribe, F., Bernal, R., and Braun, M. 2004. Descriptions of larvae of *Merluccius australis*, *Macruronus magellanicus*, and observations on a larva of *Micromesistius australis* from southern Chile (Pisces: Gadiformes). New Zealand Journal of Marine and Freshwater Research, Vol. 38: 609–619.

Ballara, S.L and O'Driscoll, R.L. 2014. Catches, size, and age structure of the 2011–12 hoki fishery, and a summary of input data used for the 2013 stock assessment. New Zealand Fisheries Assessment Report 2014/05.

Baudron, A.R., Needle, C.L., Rijnsdorp, A.D, Marshall, C.T. 2014. Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. Glob. Change Biol. 20(4): 1023–1031.

Beddington, J. R. et al. 1984. Management under uncertainty. In Exploitation of Marine Communities. R. M. May (ed.), pp. 227-244. Springer-Verlag, Berlin.

Beddington, J. R, Agnew, D. J. and Clark, C. 2007. Current Problems in the Management of Marine Fisheries. Science 316(5832), pp. 1713-1716

Beverton, R.J.H. and Holt, S.J., 1956. A review of methods for estimating mortality rates in fish populations, with special reference to sources of bias in catch sampling. Rapp. P.v. Réun. Cons. Int. Explor. Mer 140: 67–83.

Brander, K. M. 2007. Global fish production and climate change. Proc Natl Acad Sci U S A, 104, 19709-14.

Brodziak, J., and O'Brien, L. 2005. Do environmental factors affect recruits per spawner anomalies of New England groundfish? ICES J. Mar. Sci. 62: 1394-1407.

Brunel, T., and Boucher, J. 2004. Long term synchronous trends in the recruitment of the North Eastern Atlantic fish populations related to climate change and exploitation. ICES 2004 conference: session on the Regime Shifts in the North Atlantic Ocean: Coherent or Chaotic?

Brunel, T. and Boucher, J. 2007. Long term trends in fish recruitment of the north-east Atlantic related to climate change. Fish. Oceanogr. 16(4): 336-349.

Bull B, Francis R.I.C.C., Dunn A., McKenzie A., Gilbert D.J., Smith M.H., Bian, R. 2008. CASAL (C++ algorithmic stock assessment laboratory): CASAL user manual v2.20-2008/02/14. NIWA Technical Report 130. 275 p.

Burnham, K. P., and Anderson, D. R. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer. Chicago.

Butterworth, D. S., Bentley, N., De Oliveira, J. A. A., Donovan, G. P., Kell, L. T., Parma, A. M., Punt, A. E., Sainsbury, K. J., Smith, A. D. M., and Stokes, T. K. 2010. Purported flaws in management strategy evaluation: basic problems or misinterpretations? – ICES Journal of Marine Science, 67: 000–000

Caddy, J.F. 1984. An alternative to equilibrium theory for management of fisheries, pp. 63–75. In: Proceedings of the Papers Presented at the Expert Consultation on the Regulation of Fishing Effort, Fishing Mortality. Rome. January 17–26, 1983. FAO Fish. Rep. 289. Suppl. 2 (En). pp. 214.

Caputi, N., de Lestang, S., Frusher, S., & Wahle, R.A. 2013. The impacts of climate change on exploited lobster stocks. In: Lobsters: Biology, Management Aquaculture and Fisheries, Second Edition (ed: Bruce Phillips). Wiley-Blackwell Ch4: 129-165.

Castillo-Jordán, C., Klaer, N.L., Tuck, G.N., Frusher, S.D., Cubillos, L.A., Tracey, S.R., Salinger, M.J., 2016. Coincident recruitment patterns of Southern Hemisphere fishes. Can. J. Fish. Aquat. Sci. 73 (2): 270–278.

Chavez, F. P., Ryan, J., Lluch-Cota, S. E. & Niquen, C. M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science, 299, 217-21.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish. 10(3): 235-251.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., Pauly, D. 2010. Large-scale redistribution of maximum catch potential in the global ocean under climate change Glob. Change Biol. 16: 24–35.

Chong, J.V., M. Aguayo and I. Paya. 2007. Estimacion de edad , crecimiento y mortalidad natural de la merluza de cola, *Macruronus magellanicus* Lonnberg, 1907 (Macruronidae, Gadiformes) en el Oceano Pacifico Suroierntal. Rev. Biol. Mar. Oceanogr. Vol 42 (3): 311-333. Collie, J. S., Richardson, K. & Steele, J. H. 2004. Regime shifts: Can ecological theory illuminate the mechanisms? Progress in Oceanography, 60: 281-302.

Collie, J. S., Richardson, K. & Steele, J. H. 2004. Regime shifts: Can ecological theory illuminate the mechanisms? Progress in Oceanography, 60: 281-302.

Cubillos, L.A., E. Niklitschek, S. Cahuín. 2014. Relating a recruitment shift of Patagonian grenadier (Macruron magellanicus Lönnberg) to large-scale environmental changes off Southern Chile. New Zealand Journal of Marine and Freshwater Research, 48 (2). 284–293

Cubillos, L., Riquelme, K. and Ernst, B. 2009. Latitudinal changes in the Patagonian grenadier (*Macruronus magellanicus*) pelagic fishery off central-southern Chile (1986-2003). Lat. Am. J. Aquat. Res. Vol 37-2: 121-129.

Cury, P., and Roy, C.1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Can. J. Fish. Aquat. Sci. 46: 670-680.

Cury, P., Bakun, A., Crawford, R. J. M., Jarre, A., Quinones, R. A., Shannon, L. J., & Verheye, H. M. 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. ICES J. Mar. Sci. 57(3): 603-618.

Collie, J. S., Richardson, K. & Steele, J. H. 2004. Regime shifts: Can ecological theory illuminate the mechanisms? Progress in Oceanography, 60, 281-302.

Day, J. 2016. Tiger flathead (*Neoplatycephalus richardsoni*) stock assessment based on data up to 2015. Technical report presented at SERAG, Hobart, 24 November 2016.

Deser, C., Phillips, A.S., Hurrell, J.W. 2004. Pacific interdecadal climate variability: linkages between the tropics and the North Pacific during boreal winter since 1900. J Clim. 17: 3109–3124.

Dickey-Collas, M., Hintzen, N.T., Nsah, R.D.M., Schon, P.J. and Payne, M.R. 2014. Quirky patterns in time-series of estimates of recruitment could be artefacts. ICES J. Mar. Sci. doi:10.1093/icesjms/fsu022.

Doney, S.C, Ruckelshaus, M, Duffy, J.E, Barry, J.P, Chan F, English, C.A, Galindo H.M, Grebmeier, J.M, Hollowed, A.B, Knowlton, N, Polovina, J, Rabalais N.N, Sydeman, W.J, Talley, L.D. 2012. Climate change impacts on marine ecosystems. annual review of marine science, Vol 4. 4 (Carlson CA, Giovannoni SJ, Eds.).:11-37., Palo Alto: Annual Reviews.

Dunn, M.R., Hurst, R.J., Renwick J., Francis, R.I.C.C., Devine, J., McKenzie, A. 2009. Fish abundance and climate trends in New Zealand. New Zealand Aquatic Environment and Biodiversity Report No.31. 75 p.

Doney, S.C, Ruckelshaus, M, Duffy, J.E, Barry, J.P, Chan F, English, C.A, Galindo H.M, Grebmeier, J.M, Hollowed, A.B, Knowlton, N, Polovina, J, Rabalais N.N, Sydeman, W.J, Talley, L.D. 2012. Climate change impacts on marine

ecosystems. annual review of marine science, Vol 4. 4 (Carlson CA, Giovannoni SJ, Eds.).:11-37., Palo Alto: Annual Reviews.

Erzini, K. 2005. Trends in NE Atlantic landings (southern Portugal): identifying the relative importance of fisheries and environmental variables. Fish. Oceanogr. 14(3): 195–209.

Falkland Islands Government. 2013. Fisheries Department Fisheries Statistics, Volume 17, 2012: 72 pp Stanley, FIG Fisheries Department.

FAO. 1995. Precautionary approach to fisheries. Part 2: scientific papers. Prepared for the Technical Consultation on the Precautionary Approach to Capture Fisheries (Including Species Introductions). Lysekil, Sweden, 6–13 June 1995.

FAO. 2016. The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. 200 pp.

Fay, G., Punt, A. E., Smith, A. D. M. 2011. Impacts of spatial uncertainty on performance of age structure-based harvest strategies for blue-eye trevalla (*Hyperoglyphe antarctica*). Fish. Resh., 110, pp. 391-407.

Flood, M., Stobutzki, I., Andrews, J., Ashby, C., Begg, G., Fletcher, R., Gardner, C., Georgeson, L., Hansen, S., Hartmann, K., Hone, P., Horvat, P., Maloney, L., McDonald, B., Moore, A., Roelofs, A., Sainsbury, K., Saunders, T., Smith, T., Stewardson, C., Stewart, J. & Wise, B. (eds) 2013. Status of key Australian fish stocks reports 2014. Fisheries Research and Development Corporation. Canberra.

Fournier, D. A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization of Methods and Software 27:233–249.

Francis, R.I.C.C. 2017. Revisiting data weighting in fisheries stock assessment models. Fish. Res., 192: 5-15.

Francis, R.I.C.C. 2011. “Data weighting in statistical fisheries stock assessment models. Can. Journ. Fish. Aquat. Sci. 1138: 1124-1138.

Francis R. I. C. C., Hadfield M. G., Bradford-Grieve J. M., Renwick J. A., Sutton P. J. H. 2006. Links between climate and recruitment of New Zealand hoki (*Macruronus novaezelandiae*) now unclear. New Zealand Journal of Marine and Freshwater Research, 40, 547-560.

Gardner, C., Frusher, S.D., Kennedy, R.B. and Cawthorn, A. 2001. Relationship between settlement of southern rock lobster pueruli, *Jasus edwardsii*, and recruitment to the fishery in Tasmania, Australia. Mar. Freshwater Res. 52: 1271–5.

Gunn, J. S., Bruce, B. D.,Furlani, D. M., Thresher, R. E. and Blaber, S. J. M. 1989. Timing and Location of Spawning of Blue grenadier, *Macruronus novaezelandiae* (Teleostei: Merlucciidae), in Australian Coastal Waters. Aust. J. Mar. Freshwater Res., 40, 16.

Hair, Jr., J. F., Anderson, R. E., Tatham, R. L., and Black, W. C. 1984. Multivariate Data Analysis with Readings. 3th edition 1992. Prentice-Hall, Englewood Cliffs, NJ.

Haltuch, M. A., A. E. Punt. 2011. The promises and pitfalls of including decadal scale climate forcing of recruitment in groundfish stock assessment. Canadian Journal of Fisheries and Aquatic Sciences. 68(5): 912-926.

Hamer, P.A., Kemp, J., Roberston, S., Hindell, J.S. 2012. Multiple otolith techniques aid stock discrimination of a broadly distributed deepwater fishery species, blue grenadier, *Macruronus novaezelandiae*. Fisheries Research 113: 21-34.

Hilborn, R. and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty. Chapman Hall. New York.

Hilborn R. 2003. The state of the art in stock assessment: where we are and where we are going. Scientia Marina. 67 Suppl. 1:15-21.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. Rapp. P.-V. Reun. Cons. Int. Explo. Mer, 20: 1–228.

Hofmann, E.E., and Powell, T.M. 1998. Environmental variability effects on marine fisheries: Four case histories. Ecological Applications 8: 23–32.

Holmes, E.E, Ward, E.J, Wills, K. 2012. MARSS: Multivariate Autoregressive State-Space models for analyzing time-series data. The R Journal. 4(1): 11–19.

Hollowed, A.B, Hare, S.R, Wooster, W.S. 2001. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. Prog. Oceanogr. 49: 257–282.

Hollowed, A. B., Beamish, R. J., Okey, T. A., And Schirripa, M. J. 2008. Reports of PICES/NPRB workshops on forecasting climate impacts on future production of commercially exploited fish and shellfish. PICES Scientific Report, North Pacific Marine Science Organization (PICES), Sidney, British Columbia, Canada.

Horn PL, Sullivan KJ. 1996. Validated aging methodology using otoliths and growth parameters for hoki (*Macruronus novaezelandiae*) in New Zealand waters. New Zealand Journal of Marine and Freshwater Research 30: 161-174.

Hsieh, C.-H., Reiss, C. S., Hunter, J. R., Beddington, J. R., May, R. M., and Sugihara, G. 2006. Fishing elevates variability in the abundance of exploited species. Nature. 443: 859–862.

Ianelli, J., Holsman, K.K., Punt, A.E., Aydin, K, 2016. Multi-model inference for incorporating trophic and climate uncertainty into stock assessments. Deep Sea Res. II: Top. Stud. Oceanogr. Vol 134, 379-389.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.

Karoly, D., Hope, P., Jones, D. 1996. Decadal variations of the Southern Hemisphere circulation. Int. J. Climatol. 16(7): 723–738.

Kidston, J., and Gerber, E. P. 2010. Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th century climatology. Geophys. Res. Lett. 37: L09708.

King, J.R. (ed.). 2005. Report of the Study Group on Fisheries and Ecosystem Responses to Recent Regime Shifts. PICES Scientific Report No. 28. 162 pp.

King, J.R. and G.A. McFarlane. 2006. A framework for incorporating climate regime shifts into the management of marine resources. Fish. Manag. Ecol., 13. 93–102.

Klaer, N. L., O'Boyle, R. N., Deroba, J. J., Wayte, S. E., Little, L. R., Alade, L. A., Rago, P. J. 2015. How much evidence is required for acceptance of productivity regime shifts in fish stock assessments: are we letting managers off the hook? Fisheries Research, 168: 49–55.

Koslow, J.A., 1984. Recruitment patterns in northwest Atlantic fish stocks. Can. J. Fish. Aquat. Sci. 41: 1722–1729.

Kriebel, D., Tickner, J., Epstein, P., et al. 2001. The precautionary principle in environmental science. Environ Health Perspect. 109 (9): 871-876.

Krusic-Golub K, Green K, Robertson SG. 2007. Comparison of blue grenadier age composition between the CT and GABT Fisheries. Primary Industries Research Victoria, Queenscliff. Report no. 95.

Lasker, R. 1978. The relation between oceanographic conditions, and larval anchovy food in the California Current: identification of factors contributing to recruitment failure. Rapp. P.-V. Reun. Cons. Int. Explo. Mer, 173: 212–230.

Lasker, R. 1981. Factors contributing to variable recruitment of the northern anchovy (*Engraulis mordax*) in the California Current: contrasting years, 1975 through 1978. Rapp. P.-V. Reun. Cons. Int. Explo. Mer, 178: 375–388.

Leaman, B. 1991. Reproductive styles and life history variables relative to exploitation and management of Sebastes stocks. Environmental Biology of Fishes 30: 253 – 271.

Ligas, A., Sartor, P., and Colloca, F. 2011. Trends in population dynamics and fishery of *Parapenaeus longirostris* and *Nephrops norvegicus* in the Tyrrhenian Sea (NW Mediterranean): the relative importance of fishery and environmental variables. Mar. Ecol. 32(1): 25–35.

Linnane A. Gardner C. Hobday D. Punt A. McGarvey R. Feenstra J. Matthews J.et al 2010b. Evidence of large-scale spatial declines in recruitment patterns of southern rock lobster *Jasus edwardsii*, across south-eastern Australia. Fisheries Research , 105: 163–171.

Livingston, M. and Sullivan, K. 2007. Successes and challenges in the hoki fishery of New Zealand. In McClanahan TR, Castilla JC eds Fisheries management: progress towards sustainability. Singapore, Blackwell Publishing Ltd. Pp. 253-273

Livingston, M. E., Hurst, R. J., O'Driscoll, R. L., McKenzie, A., Ballara, S. L. and Horn, P. L. 2015. Biology and fisheries of New Zealand hoki (*Macruronus novaezelandiae*), in Hakes: Biology and Exploitation (ed H. Arancibia), John Wiley & Sons, Ltd, Chichester, UK.

Lloris, D., J. Matallanas, P. Oliver. 2005. Hakes of the world (family Merluciidae): an annotated and illustrated catalogue of hake species known to date FAO Species Catalogue for Fisheries Purposes, vol. 2. 69 pp

Mace, P. 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish and Fisheries 2(1): 2-32.

Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M., Hornik, K. 2014. cluster: Cluster Analysis Basics and Extensions. R package version 1.15.2.

Mann, K.H. 1993. Physical oceanography, food chains, and fish stocks: a review. ICES J. mar. Sci. 50: 105-119.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M, Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. B. Am. Meteorol. Soc. 78: 1069–1180.

Maunder, M.N., 2008. Maximum Sustainable Yield. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), General Ecology, vol. 3 of Encyclopedia of Ecology, 5 vols, Oxford: Elsevier, pp. 2292–2296.

Maunder M. N., Deriso, R. B. 2003. Estimation of recruitment in catch-at-age models. Can. J. Fish. Aquat. Sci. 60(10): 1204-1216.

Maunder, M. N. and Watters, G. M. 2003. A general framework for integrating environmental time series into stock assessment models: model description, simulation testing, and example. Fishery Bulletin, 101(1), pp. 89-99.

Maunder, M.N and Punt, A.E. 2013. A review of integrated analysis in fisheries stock assessment. Fish Res 142: 61–74.

McAllister, M.K. and Ianelli, J.N. 1997. Bayesian stock assessment using catch-age data and the sampling – importance algorithm. Can. J. Fish. Aquat. Sci. 54 pp. 284–300

McFarlane, G.A., King, J.R., and Beamish, R.J. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* 47, 147–169.

McKenzie, A. 2016. Assessment of hoki (*Macruronus novaezelandiae*) in 2015. New Zealand Fisheries Assessment Report 2016/01. 88 p.

Methot, R.D., 2000. Technical description of the Stock Synthesis assessment program. NOAA Tech Memo. NMFS-NWFSC-43.

Methot, R.D. Jr., Taylor. I.G. 2011. Adjusting for bias due to variability of estimated recruitments in fishery assessment models. Can. J. Fish. Aquat. Sci. 68: 1744-1760.

Methot, R.D. Jr, and Wetzel, C.R. 2013. Stock Synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Res. 142: 86–99.

Ministerio de Agricultura, G. Y. P. 2012. Pesca Marítima Desembarques [Online]. Available: http://www.minagri.gob.ar/site/pesca/pesca_maritima/02-desembarques/lectura.php?imp=1&tabla=especie_mes_2012. Visited 10-05-2013.

Mueter, F.J., Boldt, J.L., Megrey, B.A., and Peterman, R.M. 2007. Recruitment and survival of Northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. Can. J. Fish. Aquat. Sci. 64: 911–927.

Mueter, F.J., Bond, N.A, Ianelli, J.N., Hollowed, A.B. 2011. Expected declines in recruitment of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea under future climate change. ICES J. Mar. Sci. 68(6): 1284-1296.

Myrseth, J., Enberg, K., Heino, M., and Fiksen, O. 2011. Do accurate stock estimates increase harvest and reduce variability in fisheries yields?. Nat. Res. Model. 24: 222–241.

Ohlberger, J., Rogers, L.A., Stenseth, N.C. 2014. Stochasticity and determinism: How density-independent and density-dependent processes affect population variability. PLoS ONE 9(6): e98940. doi:10.1371/journal.pone.0098940.

O'Kane, T., Matear, R., Chamberlain, M., Risbey, J., Sloyan, B., Horenko, I. 2013. Decadal variability in an OGCM Southern Ocean: Intrinsic modes, forced modes and metastable. Ocean Model. 69: 1‑21.

Palomera, I., Olivar, M. P., Salat, J., Sabatés, A., Coll, M., Garcia, A., Morales-Nin, B. 2007. Small pelagic fish in the NW Mediterranean Sea: an ecological review. Prog. Oceanogr. 74: 377–396.

Parrish, R.H., A. Bakun, D.M. Husby, and C.S. Nelson. 1983. Comparative climatology of selected environmental processes in relation to eastern boundary current pelagic fish reproduction. In G.D. Sharp and J. Csirke (eds.), Proceedings of the expert consultation to examine changes in abundance and species composition of neritic fish resources. San Jose, Costa Rica, 18-29 April 1983. FAO Fish. Rep. 291(3):731-777

Pauly, D., V. Christensen, and S. Guénette. 2002. Towards sustainability in world fisheries. Nature 418: 689–95.

Patterson, H., Noriega, R., Georgeson, L., Stobutzki., I & Curtotti. R 2016. Fishery status reports 2016. Australian Bureau of Agricultural and Resource Economics and Sciences. Canberra. CC BY 3.0.

Payá, I. 2014. Investigación del estatus y posibilidades de explotación biológicamente sustentables de los principales recursos pesqueros nacionales año 2015. Merluza de cola, 2015. Subsecretaría de Economía y EMT – IFOP. Documento Técnico 2. Informe de estatus y cuota. 108 pp + 6 anexos.

Payá, I. & Canales , C. 2011. Chilean Hoki Stock Assessment Workshop 2011 [Online]. Available: https://sites.google.com/site/chsaw2011. Visited 05-05-2013.

Pörtner, H. O., and Knust, R. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science. 315: 95–97.

Power, S., Casey, T., Folland, C., Colman, A. and Mehta, V. 1999. Decadal modulation of the impact of ENSO on Australia. Clim. Dynam. 15: 319-324.

Prenski, L. B., Morales-Yokobori, M. L., Minte Vera, C. B., Jorge; , Landa, P., Di Giacomo, E. & Perier, M. 2012. Argentine Hoki (*Macruronus magellanicus*). Bottom And Semi Pelagic Trawl Net Fishery. In: (OIA), O. I. A. S. A. (ed.). Buenos Aires.

Punt, A.E. 2017. Some insights into data weighting in integrated stock assessments. Fish. Res., 192: 52–65.

Punt, A. E., Haddon, M., Little, L. R., and Tuck, G. N. 2016. The effect of marine closures on a feedback control management strategy used in a spatially aggregated stock assessment: a case study based on pink ling in Australia. Can. J. Fish. Aquat. Sci. 73: 1–14.

Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., and Haddon, M. 2014. Management strategy evaluation: best practices. Fish and Fisheries, doi:10.1111/faf.12104.

Punt, A.E, and Maunder, M.N. 2013. Stock Synthesis: advancing stock assessment application and research through the use of a general stock assessment computer program Preface. Fish. Res. 142:1-2.

Punt, A. E., Smith, A. D. M. and Cui, G. 2001a. Review of progress in the introduction of management strategy evaluation (MSE) approaches in Australia's South East Fishery. Mar. Freshw. Res., 52: 719–726.

Punt, A.E, Smith, D.C., Thomson, R.B., He, X., Haddon, M., Lyle, J.M. 2001b. Stock assessment of the blue grenadier *Macruronus novaezelandiae* resource off south-eastern Australia. Mar. Freshw. Res., 52 (4): 701-717.

Punt, A.E., McAllister, M., Pikitch, E. Hilborn, R., 1994. Stock assessment and decision analysis for hoki (*Macruronus novaezelandiae*) for 1994. Technical Report. New Zealand Fisheries Assessment Research Document 94/13, 47 pp.

Quinn, T.J. y S.P. Cox. 2011. Chilean hoki stock assessment workshop 2011. Workshop report. Instituto de Fomento Pesquero. P.69

R Development Core Team. 2012. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. Available from http://www.R-project.org.

Rademeyer, R.A., and Butterworth, D.S. 2013. 2013 update of the reference set of the Operating Models used in testing candidate OMPs for the South African hake resource. 7pp.

Revelle, W. 2015. psych: Procedures for Personality and Psychological Research, Northwestern University, Evanston, Illinois, USA. http://CRAN.R-project.org/package=psych Version = 1.5.4.

Rice, J.C. and Garcia, S.M. 2011. Fisheries, food security, climate change and biodiversity: characteristics of the sector and perspectives of emerging issues ICES J. Mar. Sci., 68 (6), pp. 1343–1353.

Rinjnsdorp, A.D., Peck, M.A., Engelhard, G.H., Möllmann, C. and Pinnegar, J.K. 2009. Resolving the effect of climate change on fish populations. ICES J. Mar. Sci. 66: 1570–1583.

Ropelewski, C.F., and Jones, P.D. 1987. An Extension of the Tahiti–Darwin Southern Oscillation Index. Mon. Wea. Rev. 115: 2161–2165.

Rothschild, B. J. and Osborn. T. R. 1988. Small-scale turbulence and plankton contact rates. J. Plank. Res., 10: 465–474. doi:10.1093/plankt/10.3.465

Rothschild, B. J. & Shannon, L. J. 2004. Regime shifts and fishery management. Progress in Oceanography, 60, 397-402.

Rothschild, B.J. and Jiao, Y. 2012. Characterizing variation in Northwest Atlantic fish-stock abundance. ICES J. Mar. Sci. 69: 913–922.

Roy, C., and Reason, C. 2001. ENSO-related modulation of coastal upwelling in the eastern Atralntic. Prog. Oceanogr. 49: 245-255.

Sainsbury K. J., Punt A. E., Smith A. D. M. Design of operational management strategies for achieving fishery ecosystem objectives. ICES J. Mar. Sci. 57: 731-741.

Salinger, M.J., Renwick, J.A., Mullan, A.B., 2001. Interdecadal Pacific Oscillation and South Pacific climate. Int. J. Climatol. 21(14): 1705-1721.

Salinger, J. (ed). 2013. Living in a warmer world. How a changing climate will affect our lives. CSIRO publishing, Melbourne.

Salisbury, J. I. and Wimbush, M. 2002. Using modern time series analysis techniques to predict ENSO events from the SOI time series. Nonlinear Processes in Geophysics. European Geosciences Union (EGU). 9 (3/4): 341-345.

Schneider, W., Donoso, D., Garces-Vargas, J., Escribano, R. 2017. Water-column cooling and sea surface salinity increase in the upwelling region off central-south Chile driven by a poleward displacement of the South Pacific High Progress in Oceanography 151:38-48.

Schuchert, P. C., Arkhipkin, A. I. & Koenig, A. E. 2010. Traveling around Cape Horn: Otolith chemistry reveals a mixed stock of Patagonian hoki with separate Atlantic and Pacific spawning grounds. Fisheries Research, 102, 80-86.

Shelton, A.O and Mangel,M. 2011. Fluctuations of fish populations and the magnifying effects of fishing. PNAS, 108:17. 7075-7080.

Sernapesca. 2014. Actividades de fiscalización efectuadas en materia de pesca y acuicultura en el año 2013. Servicio nacional de pesca y acuicultura. Ministerio de economia, fomento y turismo.

Shelton, A.O., and Mangel, M. 2011. Fluctuations of fish populations and the magnifying effects of fishing. P. Natl. Acad. Sci. 108(17): 7075-7080.

Smith, A. D. M., Sainsbury, K. J. and Stevens, R. A. 1999. Implementing effective fisheries-management systems –management strategy evaluation and the Australian partnership approach. ICES J. Mar. Sci., 56: 967–979.

Smith, A.D.M., Smith, D.C., Tuck, G.N. et al. 2008. Experience in implementing harvest strategies in Australia's south-eastern fisheries. Fisheries Research 94, 373–379.

Smith, P. J., and C. D. Paulin. 2003. Genetic and morphological evidence for a single species of pink ling (*Genypterus blacodes*) in New Zealand waters. New Zeal J. Mar. Fresh. 37(1): 183-194.

Stachura, M. M., N. J. Mantua, and M. D. Scheuerell. 2014. Oceanographic influences on patterns in North Pacific salmon abundance. Can. J. Fish. Aquat. Sci. 71(2): 226-235.

Steele, J. H. 1984. Kinds of variability and uncertainty affecting fisheries. In Exploitation of Marine Communities, R.M May (ed), 245-262. Springer-Verlag. Berlin.

Subbey, S., Devine, J.A., Schaarschmidt, U., and Nash, R.D.M. 2014. Modelling and forecasting stock–recruitment: current and future perspectives. ICES J. Mar. Sci. 71: 2307–2322.

Subpesca. 2016. Estado de situación de las principales pesquerías Chilenas, año 2015. Depto. Pesquerias. Div. Adm. Pesquera, Subsecretaria de Pesca y Acuicultura. pp. 95.

Sumaila, U.R., Cheung, W.W.L., Lam, V.M.Y, Pauly, D., Herrick, S. 2010. Climate change impacts on the biophysics and economics of world fisheries. Nature Climate Change, 1 (2011), pp. 449–456

Teh, L.C.L. and Sumaila, U.R. 2013. Contribution of marine fisheries to worldwide employment. Fish and Fisheries 14, 77–88.

Tascheri, R., Saavedra-Nievas, J. C. & Roa-Ureta, R. 2010. Statistical models to standardize catch rates in the multi-species trawl fishery for Patagonian grenadier (*Macruronus magellanicus*) off Southern Chile. Fisheries Research, 105, 200-214.

Taylor, I., Stewart, I., Hicks, A., Garrison, T., Punt, A., Wallace, J., Wetzel, C., Thorson, J., Takeuchi, Y., Monnahan, C., 2014. Package r4ss, (https://github.com/r4ss).

Thompson, D.W.J., Wallace, J.M., 2000. Annular modes in the extratropical circulation. Part I: Month-to-month variability. J. Clim 13: 1000–1016.

Todd, C. D., Friedland, K. D., Maclean, J. C., Whyte, B. D., Russell, I. C., Lonergan, M. E., and Morrissey, M. B. 2012. Phenological and phenotypic changes in Atlantic salmon populations in response to a changing climate. ICES J. Mar. Sci., 69: 1686–1698.

Trenberth, K.E., Stepaniak, D.P., Smith, L., 2005. Interannual variability of the patterns of atmospheric mass distribution. J. Clim. 18: 2812–2825.

Tuck, G.N. 2012. Stock Assessment for the Southern and Eastern Scalefish and Sharkfish 2011, Part 1, pp. 16–72. Ed. by G. N. Tuck. Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research

Visser, M. E., & Both, C. 2005. Shifts in phenology due to global climate change: the need for a yardstick. Proceedings of the Royal Society, Series B 272, 2561–2569.

Walters, J. 1984. Managing fisheries under biological uncertainty. *In* Exploration of marine communities. *Edited by* R.M. May. Springer-Verlag, Berlin. pp. 263–274.

Walters, C. and Maguire, JJ. 1996. Lessons for stock assessment from the northern cod collapse. Rev Fish Biol Fisheries 6: 125.

Ward, R.D., Appleyard, S.A., Daley, R.K., Reilly, A. 2001. Population structure of pink ling (*Genypterus blacodes*) from southeastern Australian water, inferred from allozyme and microsatellite analyses. Mar. Fresh. Res. 52: 965–973.

Wayte, S. E. 2013. Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus macropterus*) in south-eastern Australia. Fisheries Research, 142, 47-55.

Wayte, S.E., Klaer, N.L., 2010. An effective harvest strategy using improved catch curves. Fish. Res. 106, 310–320.

Whitten, A R., Klaer, N.L., Tuck, G.N., Day, R.W. 2013. Accounting for cohort-specific variable growth in fisheries stock assessments: A case study from south-eastern Australia. Fish. Res. 142: 27-36.

Wiff, R., Quiroz, J.C., Ojeda, V., Barrientos, M.A. 2011. Estimation of natural mortality and uncertainty in pink cusk-eel (*Genypterus blacodes* Schneider, 1801) in southern Chile. Lat. Amer. J. Aquat. Res. 39: 316–326.

Worm et al. 2006. Rebuilding global fisheries. Science 325 (5940), pp. 578-585.

Yasunaka, S. & Hanawa, K. 2005. Regime shift in the global sea-surface temperatures: its relation to El Niño-southern oscillation events and dominant variation modes. International Journal of Climatology, 25, 913-930.

Yin, J.H. 2005. A consistent Poleward shift of the storm tracks in simulations of 21st century climate. Geophys. Res. Lett. 32: L18701.

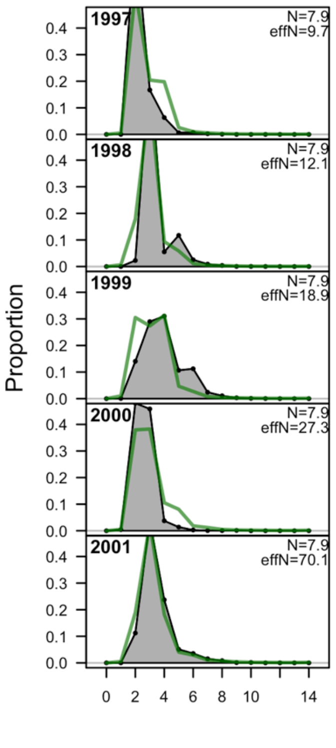
Zuur A. F, Fryer R. J, Jolliffe I. T, Dekker R, Beukema J. J. 2003a. Estimating common trends in multivariate time series using dynamic factor analysis. Environmetrics. 14: 665– 685.

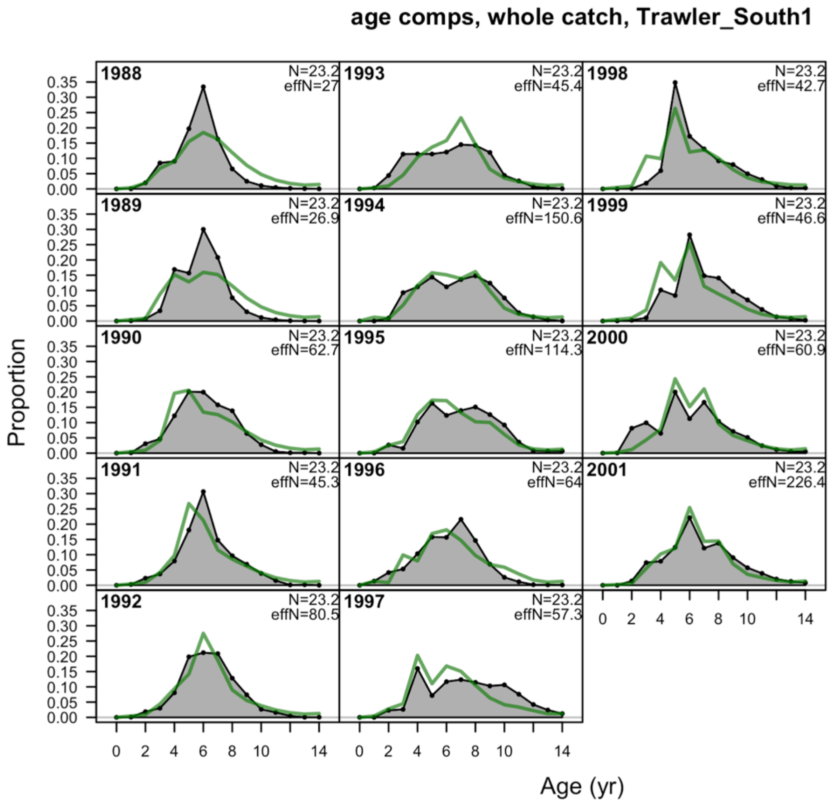
Zuur, A. F., Tuck, I. D., and Bailey, N. 2003b. Dynamic factor analysis to estimate common trends in fisheries time series. Can. J. Fish. Aquat. Sci. 60: 542-552.

Zuur, A. F., and Pierce, G. J. 2004. Common trends in Northeast Atlantic squid time series. J. Sea Res. 52: 57-72.

APPENDIX 1

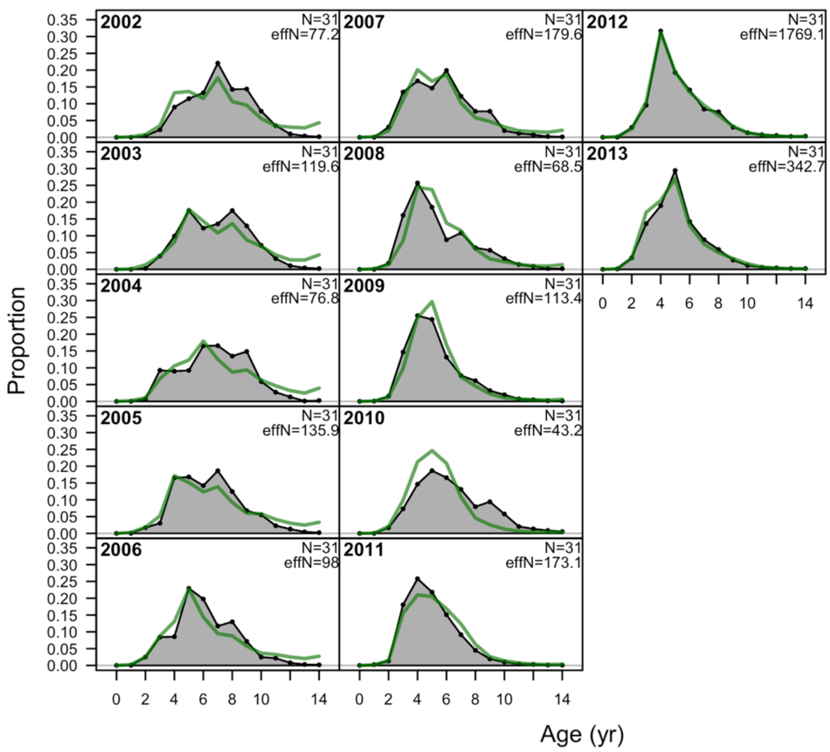
age comps, whole catch, Purse-seine



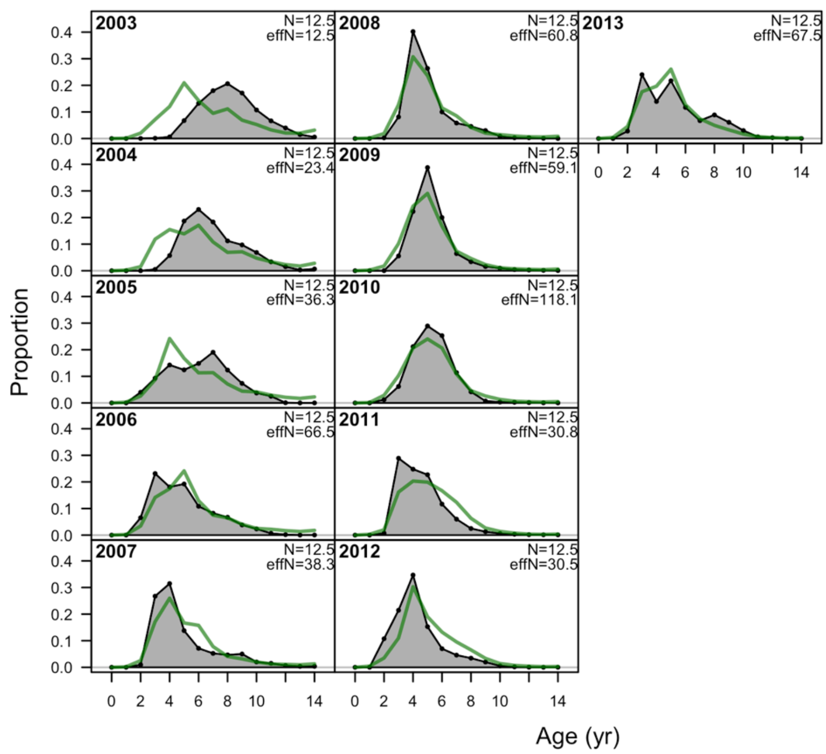


age comps, whole catch, Trawler_South1
1988
N=23.2
effN=27
1993
N=23.2
effN=45.4
1998
N=23.2
effN=42.7
1989
N=23.2
effN=26.9
1994
N=23.2
effN=150.6
1999
N=23.2
effN=46.6
1990
N=23.2
effN=62.7
1995
N=23.2
effN=114.3
2000
N=23.2
effN=60.9
1991
N=23.2
effN=45.3
1996
N=23.2
effN=64
2001
N=23.2
effN=226.4
1992
N=23.2
effN=80.5
1997
N=23.2
effN=57.3
Proportion
Age (yr)

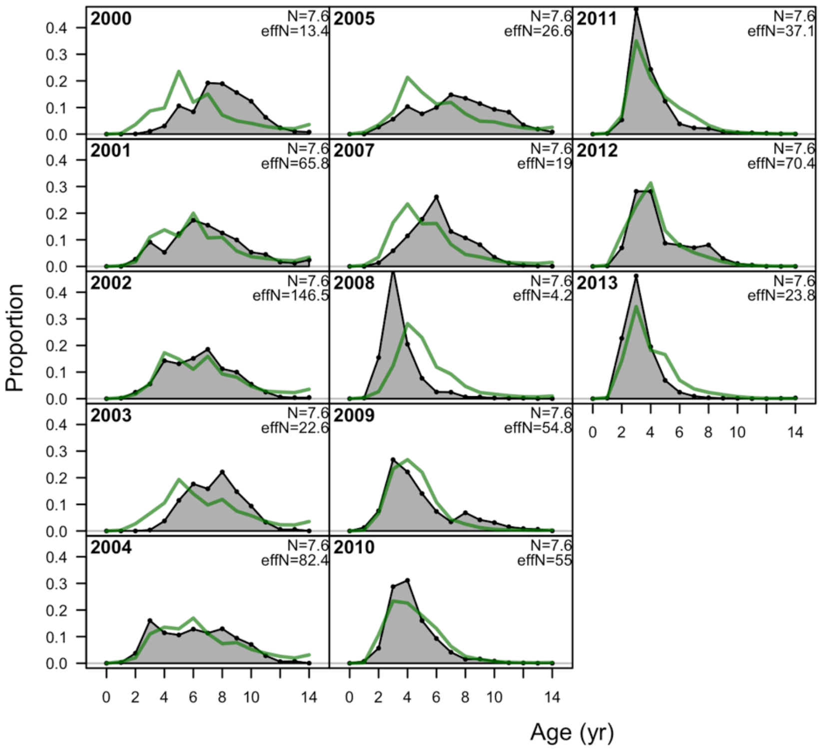
age comps, whole catch, Trawler_South2



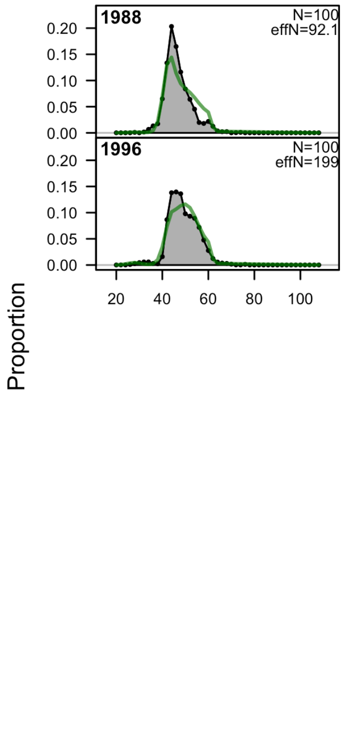
age comps, whole catch, Trawler_Centre



age comps, whole catch, Acoustic_Survey

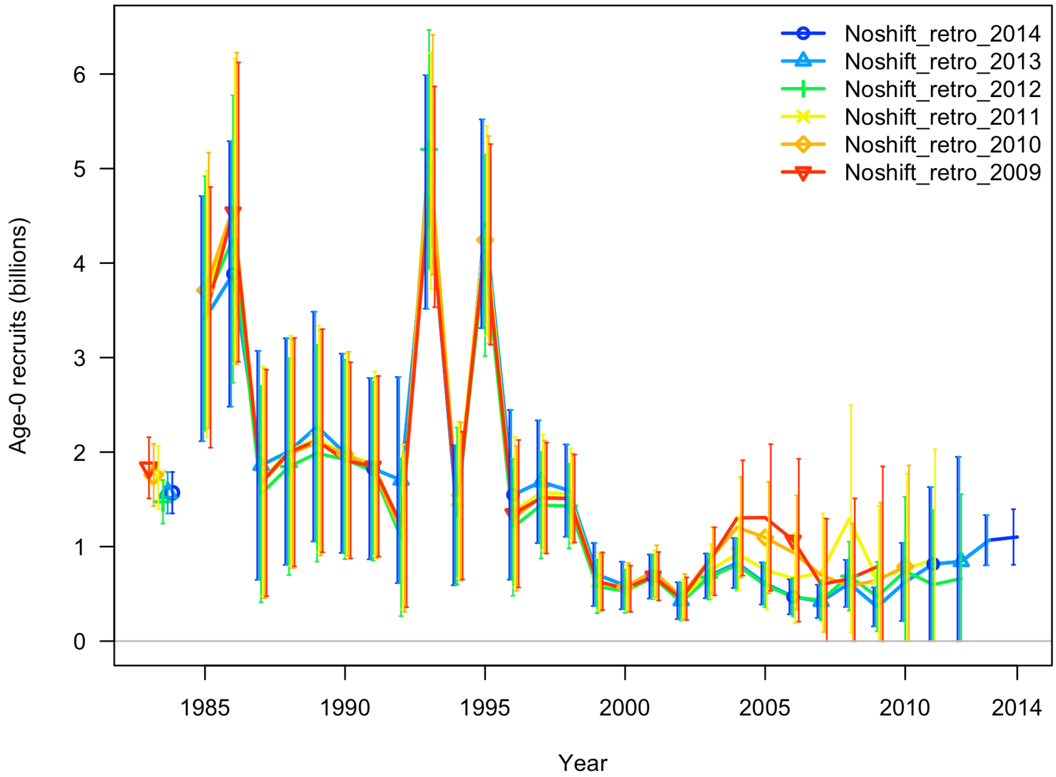


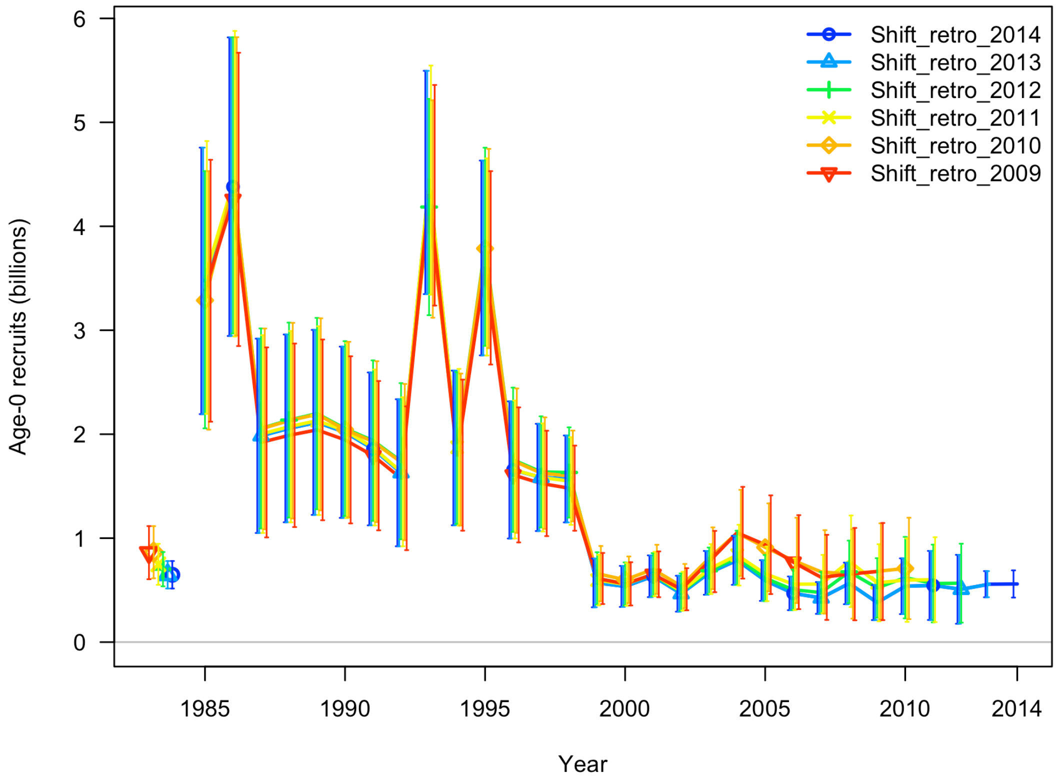
length comps, retained, Purse-seine

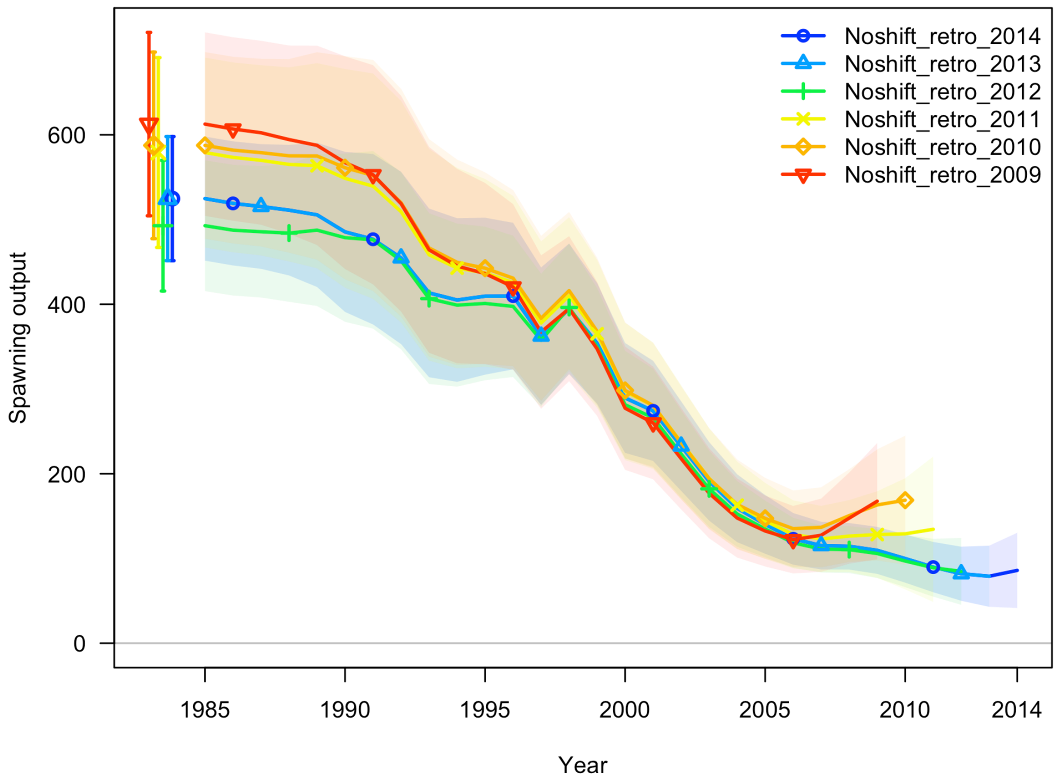


APPENDIX 2.

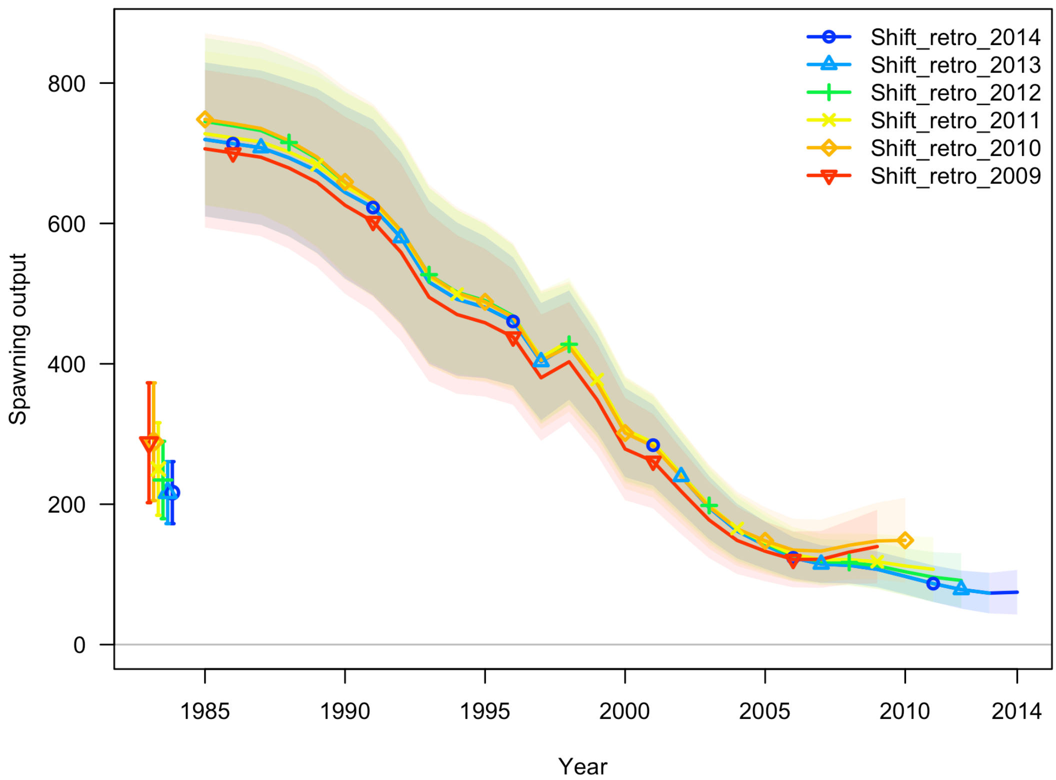
Retrospective analysis.







Noshift_retro_2014
Noshift_retro_2013
Noshift_retro_2012
Noshift_retro_2011
Noshift_retro_2010
Noshift_retro_2009
Spawning output
0
200
400
600
1985
1990
1995
2000
2005
2010
2014
Year



Shift_retro_2014
Shift_retro_2013
Shift_retro_2012
Shift_retro_2011
Shift_retro_2010
Shift_retro_2009
Spawning output
0
200
400
600
800
1985
1990
1995
2000
2005
2010
2014
Year

APPENDIX 3

#V3.24f P.Grenadier data provided by SUBPESCA CHILE for C.Castillo-Jordan PhD Thesis
#SS-V3.24f-safe-OSX;_08/03/2012;_Stock_Synthesis_by_Richard_Methot_(NOAA)_using_ADMB_11
#_Start_time: Mon July 6 16:12:32 2015
#_Number_of_datafiles: 3 new version with 4 fleet and 2 survey

#_observed data:
1985 #_styr
2014 #_endyr
1 #_nseas
12 #_months/season
1 #_spawn_seas
4 #_Nfleet (1)Purse-seine (2)trawler south1 (3)trawler south2 (4)trawler centre
1 #_Nsurveys
1 #_N_areas
Purse-seine%Trawler_South1%Trawler_South2%Trawler_Centre%Acoustic_Survey

0.5 0.5 0.5 0.5 0.5 #_surveytiming_in_season
1 1 1 1 1 #_area_assignments_for_each_fishery_and_survey
1 1 1 1 #_units of catch: 1=bio; 2=num
0.1 0.1 0.1 0.1 #0.01_se of log(catch) only used for init_eq_catch and for Fmethod 2 and 3

```
1	#_Ngenders
14	#_Nages
0	0	0	0	#0_init_equil_catch_for_each_fishery
30	#_N_lines_of_catch_to_read

#_catch_biomass(mtons):_columns_are_fisheries,year,season
#beloware	numbers
0	18720	1	1	1985	1
0	37080	1	1	1986	1
114560		17280	1	1	1987	1
191810		19820	1	1	1988	1
207210		20180	1	1	1989	1
107330		20680	1	1	1990	1
149600		15080	1	1	1991	1
196670		17660	1	1	1992	1
70950	11630	1	1	1993	1
68590	12720	1	1	1994	1
192290		14440	1	1	1995	1
360080		15370	1	1	1996	1
60200	11280	1	1	1997	1
336810		17380	1	1	1998	1
285910		24000	1	1	1999	1
74000	17340	1	1	2000	1
123290		23230	1	11630	2001	1
78810	1	26250	17710	2002	1
4020	1	36100	43710	2003	1
```

3150	1	47630	14320	2004	1
5210	1	52180	21280	2005	1
50	1	61790	10440	2006	1
20	1	48820	14450	2007	1
0	1	56600	16850	2008	1
0	1	66740	11700	2009	1
230	1	57200	16900	2010	1
630	1	42420	26700	2011	1
630	1	41800	20300	2012	1
600	1	35993	11667	2013	1
630	1	30196	9804	2014	1

#

37 #39 40_N_cpue_and_surveyabundance_observations_Chile

#Units:0=numbers; 1=biomass; 2=F

#Errtype: -1=normal; 0=lognormal; >0=T

#Fleet	Units	Err_Type	
1	1	0	#purse seine
2	1	0	#trawlSouth1
3	1	0	#trawlSouth2
4	1	0	#trawlCentre
5	1	0	#Acoustic_survey

#Year	seas	index	obs	se(log)			
#1988	1	1	171.39	0.5	#cpue	Purse	sein0.1
#1989	1	1	157.85	0.5			

#1990	1	1	120.29	0.5			
#1991	1	1	133.59	0.5			
#1992	1	1	132.15	0.5			
#1993	1	1	90.02	0.5			
#1994	1	1	115.57	0.5			
#1995	1	1	114.63	0.5			
#1996	1	1	109.67	0.5			
#1997	1	1	76.54	0.5			
#1998	1	1	84.48	0.5			
#1999	1	1	124.23	0.5			
#2000	1	1	142.2	0.5			
#2001	1	1	128.87	0.5			
#2002	1	1	95.01	0.5			
1985	1	2	1	0.4	#cpue Trawler	South1 est	chile
1986	1	2	0.769711701	0.4			
1987	1	2	0.808382969	0.4			
1988	1	2	0.565339406	0.4			
1989	1	2	0.498037129	0.4			
1990	1	2	0.453955112	0.4			
1991	1	2	1.077549217	0.4			
1992	1	2	1.169878155	0.4			
1993	1	2	0.994021587	0.4			
1994	1	2	0.513904771	0.4			
1995	1	2	1.057447661	0.4			
1996	1	2	1.274449776	0.4			
#1997	1	2	0.058000	0.4			

#1998	1	2	0.104000	0.4	
#1999	1	2	0.166000	0.4	
#2000	1	2	0.179000	0.4	#trawler south2
#2001	1	2	0.384000	0.4	#change from
2002	1	3	1.000000	0.3	#Cpue survey 2001 or 2002???
2003	1	3	0.855580277	0.3	
2004	1	3	0.448498098	0.3	
2005	1	3	0.3320409	0.3	
2006	1	3	0.446736388	0.3	
2007	1	3	0.411278906	0.3	
2008	1	3	0.639036314	0.3	
2009	1	3	0.588198205	0.3	
2010	1	3	0.502688876	0.3	
2011	1	3	0.435811609	0.3	
2012	1	3	0.394782402	0.3	
2013	1	3	0.346624223	0.3	
2000	1	5	501300	0.3	#acoustic survey0.3
2001	1	5	577900	0.3	
2002	1	5	433700	0.3	
2003	1	5	245600	0.3	
2004	1	5	188000	0.3	
2005	1	5	145100	0.3	
2007	1	5	163200	0.3	
2008	1	5	231200	0.3	
2009	1	5	251500	0.3	
2010	1	5	208300	0.3	

```
2011	1	5	220900	0.3
2012	1	5	162266	0.3
2013	1	5	132370	0.3


0	#_N_fleets_with_discard
#_discard_units	(1=same_as_catchunits(bio/num);	2=fraction;	3=numbers)
#_discard_errtype:	>0	for	DF	of	T-dist(read	CV	below);	0	for	normal with	CV;	-1	for
	normal with	se;	-2	for	lognormal

#_Fleetunits	errtype
#1	2	-1	#purse seine
0	#_N_discard_obs
#_year seas	fleet	obs	err
#
0	#_N_meanbodywt_obs
30	#_DF_for_meanbodywt_T-distribution_like
1	#	length bin	method:	1=use	databins;	2=generate	from	binwidth,min,max	below; 3=read vector
#	no	additional	input	for	option 1
#	read	binwidth,	minsize,	lastbin size	for	option 2
#	read	N	poplen bins,	then	vector of	bin	lower	boundaries,	for	option 3
-1	#_comp_tail_compression
0.0001 #_add_to_comp
1	#_combine	males	into	females	at	or	below	this	bin	number
45	#_N_LengthBins
```

20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58
60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100 102 104 106 108

2 #N-lenghts lines
Yr Seas Flt/Svy Gender Part Nsamp datavector(female-male)
1988 1 1 0 2 100 0 0 0 0 0.000804573 0 0.001551146 0.006542178 0.013301487
0.017322867 0.065174909 0.13400981 0.204028518 0.165554739 0.11659771 0.084156001 0.064252847 0.04540709
0.019864487 0.018006978 0.021808253 0.012554915 0.003659991 0.002113307 0.002262026 0 0.000221592
0.000804573 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1996 1 1 0 2 100 0 0.000073 0.000073 0.000926 0.002562 0.004484 0.005776
0.005829 0.003011 0.00235 0.015899 0.086925 0.138624 0.140103 0.136624 0.098258
0.093534 0.089552 0.072212 0.047727 0.027767 0.012353 0.00555 0.003699 0.002985
0.001551 0.000238 0.000119 0.001194 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

15 #_N_age_bins
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

1 #_N_ageerror_definitions

0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5 10.5 11.5 12.5 13.5 14.5
0.153649 0.153649 0.153649 0.220276 0.289405 0.361129 0.435546 0.512757 0.592866 0.675983
0.762221 0.851697 0.944532 1.04085 1.14079

55 #_N_Agecomp_obs

2 #_Lbin_method: 1=poplenbins; 2=datalenbins; 3=lengths

1 #_combine males into females at or below this bin number

Yr Seas Flt/Svy Gender Part Ageerr Lbin_lo Lbin_hi Nsamp datavector(female-male)

#Yr Seas Flt/Svy Gender Part Ageerr Lbin_lo Lbin_hi Nsamp datavector(female-male)
1997 1 1 0 0 1 -1 -1 100 0 0 0.751584015 0.167321511 0.063511026 0.006805069
0.007274079 0.002592829 0.000911472 0 0 0 0 0 0

1998 1 1 0 0 1 -1 -1 100 0 0 0.02276528 0.76520439 0.055213876 0.117384612
0.025457812 0.008860354 0.004067068 0.000419648 0.000378186 0.000173388 7.54E-05 0 0

1999 1 1 0 0 1 -1 -1 100 0 0.000518327 0.1406569 0.290081527 0.310542581
0.106699711 0.112484416 0.023941246 0.010711075 0.00304498 0.000881004 0.000362677 7.56E-05 0 0

2000 1 1 0 0 1 -1 -1 100 0 0.004106456 0.480377266 0.458824377 0.037480413
0.013799252 0.002833695 0.000621372 0.000546327 0.001359813 0 0 5.10E-05 0 0

2001 1 1 0 0 1 -1 -1 100 0 0 0.112328767 0.53781878 0.237610661 0.05082782
0.035308918 0.015546858 0.008315472 0.000928773 0.00131395 0 0 0 0

1988 1 2 0 0 1 -1 -1 100 0 0.000156636 0.019991134 0.08496189 0.090661316
0.197237494 0.334624152 0.163586125 0.065450621 0.024956341 0.010787349 0.004799401 0.001862618 0.000809605
0.00011532

1989 1 2 0 0 1 -1 -1 100 0 0.00084039 0.007030804 0.033644223 0.169041312
0.157195135 0.300513628 0.208315004 0.076121235 0.030320562 0.011405951 0.004243522 0.000972771 0.000339158
1.63E-05

1990 1 2 0 0 1 -1 -1 100 0 0.001066816 0.030985803 0.046643809 0.122464825
0.20162131 0.200004268 0.158251937 0.138866928 0.064689982 0.027682024 0.005259262 0.001160397 0.001302639 0

1991 1 2 0 0 1 -1 -1 100 0 0.002635914 0.02313258 0.036991532 0.079354762
0.180814253 0.306900175 0.147825644 0.096447487 0.068722538 0.038763819 0.015428503 0.001164195 0.001818598 0

1992 1 2 0 0 1 -1 -1 100 0 0.000774893 0.018629346 0.030100097 0.080628599
0.198440923 0.212066307 0.208844482 0.128383059 0.073876872 0.026582328 0.016039382 0.00475819 0.000380451
0.000495071

1993 1 2 0 0 1 -1 -1 100 0 0.003023829 0.044057108 0.113989163 0.114696026
0.114415536 0.120731362 0.14518265 0.142665919 0.119500665 0.044226181 0.026118107 0.006989181 0.003664749
0.000739523

1994 1 2 0 0 1 -1 -1 100 0 6.97E-05 0.009807544 0.09303388 0.111988663
0.144051171 0.111969435 0.136120932 0.148107629 0.124410471 0.075555057 0.027023031 0.013786904 0.003680836

0.00039478

1995 1 2 0 0 1 -1 -1 100 0 0.000219241 0.026688935 0.015957029 0.102112265
0.163789027 0.123652506 0.139787346 0.151259389 0.126384928 0.092251383 0.03608882 0.007982864 0.006855214
0.006971052

1996 1 2 0 0 1 -1 -1 100 0 0.013422819 0.041592429 0.053299712 0.103426537
0.158085328 0.157082963 0.21612256 0.146598932 0.068938767 0.025883042 0.01137039 0.001883456 0.001454139
0.000838926

1997 1 2 0 0 1 -1 -1 100 0 3.98E-05 0.022875606 0.026300659 0.160113688
0.071648096 0.117018957 0.123665026 0.114562233 0.103008821 0.106491691 0.075849823 0.042095681 0.024036389
0.012293535

1998 1 2 0 0 1 -1 -1 100 0 0 0.001110336 0.018712794 0.05958633 0.348619406
0.172553819 0.131186656 0.091950324 0.079759061 0.04969332 0.030661168 0.009687367 0.003402789 0.00307663

1999 1 2 0 0 1 -1 -1 100 0 5.78E-04 0.00261995 0.010688409 0.101709229
0.083714403 0.282645866 0.148382445 0.140930561 0.097067728 0.069036444 0.037800636 0.013855524 0.008495532
0.002474982

2000 1 2 0 0 1 -1 -1 100 0 0.000501938 0.081626993 0.099513861 0.064947986
0.200194529 0.113077178 0.16671514 0.104276057 0.071179138 0.051412752 0.024435639 0.011633721 0.005679259
0.004805809

2001 1 2 0 0 1 -1 -1 100 0 0 0.013869141 0.074065806 0.078719877 0.124616003
0.221449152 0.1217262 0.137756804 0.090545393 0.057363298 0.03890454 0.020263214 0.012682015 0.008038557

2002 1 3 0 0 1 -1 -1 100 0 0 0.003828881 0.022512818 0.089861409 0.115237328
0.132454982 0.221037428 0.142796063 0.143813961 0.077907122 0.034741245 0.010170269 0.004043366 0.001595127

2003 1 3 0 0 1 -1 -1 100 0 0 0.002701513 0.039328799 0.098751532 0.175080415
0.122862521 0.135448161 0.175074032 0.129494727 0.07147571 0.032132272 0.010972418 0.004391077 0.002286824

2004 1 3 0 0 1 -1 -1 100 0 0.000236532 0.007524586 0.092514317 0.089668238
0.092311912 0.165259729 0.165941986 0.134828518 0.148602735 0.059129859 0.027237249 0.013297725 0.000956049
0.002490565

2005 1 3 0 0 1 -1 -1 100 0 0.000285681 0.017013507 0.030317269 0.164974943
0.168199545 0.142244215 0.186727722 0.124610459 0.067707391 0.055321483 0.023052999 0.012961341 0.004321864
0.00226158

2006 1 3 0 0 1 -1 -1 100 0 0.000316731 0.025026355 0.084033713 0.085670891
0.229636839 0.197759124 0.117487616 0.129945047 0.071573783 0.024828368 0.021519579 0.007797285 0.002849113
0.001555556

2007 1 3 0 0 1 -1 -1 100 0 5.18E-05 0.0304756 0.134770274 0.167943309
0.146655502 0.199153728 0.122783332 0.077370659 0.077533311 0.019907778 0.011746694 0.007932885 0.002354214
0.001320928

2008 1 3 0 0 1 -1 -1 100 0 4.29E-06 0.018514303 0.161103284 0.257501788
0.185271603 0.087995299 0.108481638 0.06411171 0.056877374 0.032039474 0.014518568 0.008919717 0.002535516
0.00212544

2009 1 3 0 0 1 -1 -1 100 0 0.000705265 0.015661106 0.146886936 0.25527539
0.244139745 0.131721375 0.076959526 0.061561442 0.03198884 0.019525317 0.007467318 0.004914998 0.001898275
0.001294466

2010 1 3 0 0 1 -1 -1 100 0 0.00E+00 0.016779156 0.073113508 0.146596644
0.186861568 0.166074021 0.131128259 0.079558548 0.094248641 0.057768012 0.020415443 0.013478215 0.008548316
0.005429668

2011 1 3 0 0 1 -1 -1 100 0 0.002284281 0.013239904 0.180728472 0.258400206
0.218397924 0.151114621 0.091643236 0.045144373 0.01932288 0.010133424 0.004334277 0.003219177 0.001152022
0.000885202

2012 1 3 0 0 1 -1 -1 100 0 0.000421612 0.029530934 0.09571823 0.316666183
0.193244825 0.141259847 0.084030638 0.075998624 0.030199228 0.013860343 0.007703647 0.005584814 0.002572208
0.003208869

2013 1 3 0 0 1 -1 -1 100 0 0.001276105 0.034519859 0.136230625 0.189513041
0.294477615 0.142423422 0.08810677 0.059182793 0.02773781 0.011718712 0.005884531 0.004338004 0.002193872
0.002396841

2003 1 4 0 0 1 -1 -1 100 0 0 0.000285306 0.001181978 0.006228632 0.067473951
0.132380927 0.180132379 0.206404692 0.171294758 0.107511854 0.066598352 0.03986536 0.015019144 0.005622666

2004 1 4 0 0 1 -1 -1 100 0 0 0 0.005087048 0.057228565 0.187060988
0.230500146 0.183372622 0.112372899 0.097242562 0.06858701 0.033719836 0.01512075 0.002991425 0.006716147

2005 1 4 0 0 1 -1 -1 100 0 0 0.040074914 0.093063557 0.142795927 0.124405012
0.14850894 0.190626037 0.123632273 0.073467596 0.03735727 0.025163597 0.000763453 3.92E-05 0.000102245

2006 1 4 0 0 1 -1 -1 100 0 0.000145483 0.065365287 0.231712765 0.181290523
0.192434394 0.108658361 0.082436163 0.067251008 0.038295303 0.023332132 0.006824065 0.001820571 0.000115559
0.000318387

2007 1 4 0 0 1 -1 -1 100 0 0 0.009484219 0.267751789 0.315051988 0.138061409
0.071524802 0.052402982 0.046744623 0.050001751 0.020052972 0.015054249 0.006710953 0.003536324 0.003621938

2008 1 4 0 0 1 -1 -1 100 0 0 0.002613382 0.081219676 0.402601876 0.264115112
0.100137261 0.058400843 0.04570181 0.030008334 0.00874742 0.002778929 0.002873421 0.000599601 0.000202336

2009 1 4 0 0 1 -1 -1 100 0 0 0.000224326 0.055408843 0.222915272 0.388283241
0.200133969 0.064510838 0.033919309 0.015713761 0.009493037 0.004405863 0.002781519 0.001454107 0.000755915

2010 1 4 0 0 1 -1 -1 100 0 0 0.012338561 0.061943407 0.211791038 0.289537657
0.253140883 0.114168232 0.041948202 0.007221628 0.003334057 0.002522186 0.001453069 0.000536555 6.45E-05

2011 1 4 0 0 1 -1 -1 100 0 0 0.007254447 0.289346695 0.248209786 0.227349402
0.116687996 0.060109164 0.024877407 0.012996873 0.005868149 0.003374494 0.00166595 0.001334191 0.000925447

2012 1 4 0 0 1 -1 -1 100 0 0 0.107594744 0.214750827 0.347228784 0.153027376
0.07009809 0.045844571 0.034444607 0.019808605 0.005255384 0.001601047 0.00025762 6.45E-05 2.39E-05

2013 1 4 0 0 1 -1 -1 100 0 0 0.027864093 0.240458688 0.139351183 0.217359684
0.117177847 0.067430258 0.088869925 0.061168559 0.029946724 0.006557336 0.003364843 0.00017918 0.000271678

2000 1 5 0 0 1 -1 -1 100 0 0 0.000953458 0.010979536 0.030533025 0.106324305
0.083870685 0.192568573 0.189727375 0.156353778 0.123648498 0.063244784 0.023900039 0.010142152 0.007753794

2001 1 5 0 0 1 -1 -1 100 0 1.36E-05 0.027007008 0.091216218 0.053008038
0.123168728 0.17376511 0.155074133 0.12581611 0.099680558 0.053242704 0.045093648 0.016360598 0.012360723
0.024192835

2002 1 5 0 0 1 -1 -1 100 0 0.001747064 0.024217274 0.055610699 0.142894899
0.131394833 0.151517887 0.185603292 0.112257511 0.099922849 0.054529981 0.025096389 0.006378704 0.00421317
0.004615448

2003 1 5 0 0 1 -1 -1 100 0 0 0 0.00361474 0.037536262 0.114846247
0.176659255 0.158677467 0.22191416 0.14796896 0.093701715 0.033305907 0.005842822 0.005881525 5.09E-05

2004 1 5 0 0 1 -1 -1 100 0 0.002961103 0.037490981 0.160410048 0.114498637
0.106314398 0.128310073 0.113470346 0.129548676 0.094398686 0.070658684 0.028288793 0.006058973 0.007399752

0.000190849

2005 1 5 0 0 1 -1 -1 100 0 0.000223317 0.02685758 0.056349607 0.103584696
0.076521349 0.10038015 0.1481769 0.13501249 0.114763339 0.093234574 0.082838388 0.034662101 0.019223028
0.00817248

2007 1 5 0 0 1 -1 -1 100 0 1.14E-05 0.013822148 0.058810731 0.114759705
0.177490334 0.261386305 0.131358024 0.107170134 0.081629383 0.034790116 0.012671552 0.004042477 0.001448854
0.000608816

2008 1 5 0 0 1 -1 -1 100 0 0.002550089 0.154635062 0.491397858 0.204823038
0.076670278 0.02530878 0.024388614 0.006819231 0.006377575 0.002654729 0.001759917 0.001988 0.000411969
0.00021486

2009 1 5 0 0 1 -1 -1 100 0 0.012856658 0.075597445 0.267946874 0.222102499
0.140727344 0.073306342 0.03434209 0.068484437 0.041790205 0.031395506 0.015591685 0.008861288 0.00637111
0.000626517

2010 1 5 0 0 1 -1 -1 100 0 0.007294357 0.056525551 0.287843467 0.311578245
0.160224363 0.092899173 0.041521519 0.015019218 0.01613318 0.008054143 0.001756915 0.000943226 0.000206644 0

2011 1 5 0 0 1 -1 -1 100 0 0.002520586 0.053386147 0.469895811 0.24335541
0.123669411 0.038433 0.023503636 0.021078022 0.008747617 0.005361584 0.004704351 0.003387499 0.001358404
0.000598521

2012	1	5	0	0	1	-1	-1	100	0	0.001501192	0.069789459	0.282343539	0.282206814
	0.087469062	0.079956742	0.070487431	0.080578566	0.029502669	0.010848826	0.004995531	0.000320169	0	0.00E+00			
2013	1	5	0	0	1	-1	-1	100	0	0.002248175	0.227130727	0.461664633	0.195232504
	0.068787603	0.024360225	0.009437251	0.003699076	0.001936471	0.001339381	0.000210233	9.10E-05	0.001167889				
	2.69E-03												

0	#_N_MeanSize-at-Age_obs		
0	#	1	_N_environ_variables
0	#	19	_N_environ_obs

#1980	1	1
#1981	1	1
#1982	1	1
#1983	1	1
#1984	1	1
#1985	1	1
#1986	1	1
#1987	1	1
#1988	1	1
#1989	1	1
#1990	1	1
#1991	1	1
#1992	1	1
#1993	1	1

#1994 1 1
#1995 1 1
#1996 1 1
#1997 1 1
#1998 1 1

0 # N sizefreq methods to read

0 # do tags If this value is 0, then omit all entries below

0 # no morphcomp data

999
ENDDATA